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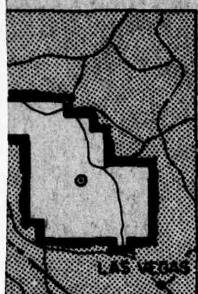

NEVADA TEST SITE
MAY-OCTOBER 1957

Test Group 57, Program 72

BIOMEDICAL AND AEROSOL STUDIES ASSOCIATED WITH A FIELD RELEASE OF PLUTONIUM

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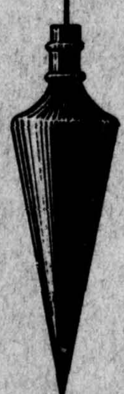

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Operation Plumbbob - Test Group 57, Program 72

BIOMEDICAL AND AEROSOL STUDIES ASSOCIATED WITH A FIELD RELEASE OF PLUTONIUM

By

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and J. Newell Stannard

University of Rochester Atomic Energy Project
Rochester, New York
November 1960

ABSTRACT

On April 24, 1957, a high-explosive detonation was employed at the Nevada Test Site to release plutonium for field study of this fissile material as a contaminant. One of four major measurement programs was a biomedical experiment which comprised exposure of animals to first deposition of plutonium oxide from the detonation cloud (acute subjects) and to the wind-induced resuspension of contamination (chronic subjects) as long as six months after original deposition.

Acute subjects (26 dogs and 40 rats) were arrayed 500, 1000, and 2000 feet downwind from ground zero, and nine rats were flown on balloon cables positioned to intercept the cloud 500 feet from ground zero. Chronic subjects (three groups of 24 dogs and 3 burros) were placed, after a rough ground-activity survey, at climatologically probable downwind segments of isopleths marking nominal contaminations of 1000, 100 and 10 μgm of plutonium per square meter. Serial sacrifices of dogs were made at 4, 5, 16, 32, 64, 128, and 161 days after detonation. Ten tissues per animal were assayed by radiochemistry and autoradiography for plutonium content. All burros received the full 161-day exposure. Ten sheep were distributed among the three field positions on the 32nd day, at which time four additional dogs were placed at the middle position (100-line). All late animals stayed until the end of the maximum exposure period. Air samplers at each chronic field position documented daily mean air concentrations.

The pattern of plutonium uptake was surprising in that statistically important numbers of acute and chronic animals showed significant bone burdens in an exposure situation for which lung alone was to have been the critical organ. This outcome was most unusual for acute animals sacrificed less than four hours postdetonation. In general, however, all uptakes were less than the forecast amounts. The factor of 100 difference between ground-level contamination at near and far chronic stations brought uptake differences of less than a factor of ten to indicate that airborne material accumulates along the upwind path. Air concentrations bear small if any relation to the "at foot" contamination for natural resuspension forces (wind).

An explanation is advanced for the fact that, in an experiment designed to find time dependence in plutonium uptake, no tissues measured exhibited a correlation with exposure time, save GI tract and contents.

The plutonium found in bone suggests some deviation from the pure oxide form (extremely insoluble in body fluids) and the presence of solubilizing influences either in early particulate formation or in animal lung. As yet no believable mechanism has been proposed. All autoradiography gave negative results.

ACKNOWLEDGMENTS

It is important that contributions made by Sandia Corporation personnel towards the success of this program be recognized. In particular, the work accomplished by William Kingsley, Supervisor of the Industrial Hygiene Division, and by his analytical section under Robert Elsbrock, should be emphasized. Literally thousands of tissue and air samples were prepared for plutonium analysis, a notoriously tedious job.

Activity analysis of the prepared samples was carried out under the direction of Harold Rarrich, also of the Industrial Hygiene Division, following a counting procedure developed by Dr. George Steck of the Analysis Division. Dr. Joan Longhurst of the Nuclear Burst Studies Division provided an evaluation of tissues (Appendix A) based on autoradiographic studies. The efforts of these and others of Sandia contributed materially to the successful conclusion of Program 72.

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Chapter 1

INTRODUCTION AND BACKGROUND

1.1 INTRODUCTION

Considerable discussion has centered around the problem of acceptable levels of ground contamination when the contaminating agent is plutonium. The development of weapons with plutonium-bearing components has led to increased concern over this problem, particularly with regard to transportation and storage. The Nuclear Safety Working Group, which is made up of representatives of the Atomic Energy Commission, the Department of Defense, and various contractors, is charged with establishing criteria for both of these situations, and in the past has been forced to do so primarily on conjectural and hypothetical bases.

In 1956, an experimental detonation was carried out in Area 11, east of Yucca Lake, at the Nevada Test Site. This test served chiefly to indicate the complexity of the problem of evaluating the phenomena associated with a release of this nature. Consequently, when the decision was made by AEC and DOD to repeat the experiment, it was with prior knowledge of the required scope of such a test, and plans were laid for an unusually extensive field operation.

1.2 BACKGROUND

As originally conceived, the experiment called for release and dispersal of plutonium by detonation of conventional high explosive, simulating a nonnuclear explosion of an assembled plutonium-bearing weapon. As planning progressed, four distinct programs began to evolve: (1) a study of cloud behavior and particulate physics; (2) a biological study to aid in evaluation of health hazards; (3) a study of decontamination procedures which might be used in the event of an accidental detonation; and (4) a study of monitoring procedures which might be useful in quickly delineating the extent of spread of contamination.*

In the early planning stages, representatives of the University of Rochester Atomic Energy Project were asked to act as consultants to the biological program, with some other organization actually performing the work. As time went on, it became evident that the University of Rochester was the only organization not already involved in Operation Plumbbob capable of performing studies of this kind.

As a consequence, in early February 1957, the University was requested by the Atomic Energy Commission to undertake the biomedical program for Test Group 57. The first ready date was April 10, 1957.

Generous support was given both by the Atomic Energy Commission and by the Department of Defense. The latter, in addition to supplying part of the funding, provided two veterinary officers and a number of enlisted men to perform the work in this program. As finally constituted, Program 72 of Test Group 57 consisted of Dr. J. Newell Stannard, Program Director; Robert H. Wilson, Director of Field Operations; Dr. Robert G. Thomas, Director of Laboratory Operations; Lt. Col. Roy Kyner, USAF veterinarian; and Capt. Ralph Thomas, U. S. Army veterinarian. The enlisted personnel (approximately 20) were about evenly divided between Air Force and Army Veterinary Corps. Sfc. Warren A. Gramly was Noncommissioned Officer in Charge of enlisted personnel.

Test Group 57 was under the direction of Dr. James D. Shreve, Jr. of Sandia Laboratory. Results of the other three programs of TG-57 are contained in other reports.[1, 2, 3, 4]

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*These were designated as Programs 71, 72, 73, and 74, respectively.

Chapter 2

EXPERIMENTAL DESIGN

Early in the planning stages of the experiment it was recognized that there were three clear-cut types of exposure which should be simulated: (a) the acute situation, resulting from exposure to the cloud for the duration of its passage, with subsequent evacuation; (b) the chronic case, resulting from reinhabiting the area an indeterminate time after cloud passage; and (c) the combination case, with exposure to both the initial cloud and subsequently resuspended material.

Each of these cases represents a possible situation with regard to human exposure following an accidental release; an evaluation of each was expected to provide information of benefit in determining the hazard to different populations (i. e., transients in the path of the cloud, decontamination crews sent in to remedy the situation, or permanent residents in the fallout pattern) exposed to such an accident.

2.1 INITIAL STAGES

Operationally, logistics is a vital part of successful field experiments, and particularly was this true for Program 72 of TG-57 because of its biological aspects. First, the Nevada Test Site is remote from biological supply houses, and second, support facilities at the site, while extensive, are primarily mechanical and physical in nature and were not geared to biological studies of the type required for this test.

As a consequence, it was necessary to anticipate needs to the utmost, and over 10,000 pounds of supplies, ranging from string and masking tape to surgical instruments and equipment, were collected in Rochester. To this accumulated material were added 83 dogs (beagle or beagle-type). Two enlisted men from the U. S. Army Veterinary Corps were assigned to the program to care for the dogs prior to and during shipment.

In order that the animals be subjected to a minimum of hardship in transit, a Flying Tiger C-46 was chartered to fly them, together with all supplies and four attendants, from Buffalo, N. Y. to Indian Springs Air Force Base, twenty miles east of Mercury, Nevada. The dogs were housed in specially constructed, heavy corrugated cardboard boxes lined with 1/2-inch hardware cloth, 15 inches wide, 24 inches long, and 22 inches high. These boxes were designed with disposal in mind, since it was anticipated that they would also be used in the test field and hence would be liable to heavy contamination. The philosophy of disposal, therefore, seemed preferable to decontamination. These boxes served well, except that certain unusually resourceful dogs managed to escape from several boxes by popping the staples loose.

The flight was uneventful, save for a 24-hour delay, caused by a defective carburetor, and the escape of two or three dogs from their boxes (though still in the plane). Transhipment to Mercury was accomplished with the help of DOD motor pool personnel and equipment.

The program was permitted to set up in existing animal facilities erected by the Civil Effects Test Group until such time as facilities specifically for Program 72 could be established. In addition to an operations building (the "Mouse House"), the CETG facilities included a dog kennel and a sheep pen which was modified for dog quarters. For the most part, dogs were quartered two to a cage. The kennel had outside runs for each cage, while the modified sheep pen provided two large fenced areas for exercise yards into which the sex-segregated dogs were released while their cages were cleaned.

A second group of 26 dogs was procured from the dog colony at the University of California Agricultural School at Davis through the kindness and cooperation of Prof. A. C. Anderson. These dogs were transported by an all-night truck run from Davis to Mercury; the special boxes were used on this run. Again, the transport was uneventful, save for a burnt-out coil in the truck which led to a four-hour delay.

It was recognized that most of the eastern dogs would need acclimatization to the desert environment if sickness was to be avoided. These dogs, in general, had come from heated kennels, and in late March and early April the Nevada weather was still rather inclement. Fortunately, the CETG kennel was heated and the dogs most likely to be adversely affected by bad weather, on the basis of their histories, were installed in the kennel at an initial temperature of 72 to 75 degrees F. On mild days, they were permitted access to the runs.

Within a few days, after it was ascertained that the travel had wrought no hardships on them, the temperature in the kennel was gradually reduced a few degrees each day, and essentially ad lib access to the runs was permitted.

Although the sheep pen was unheated and open on one side, each dog cage had houses for the animals, and it was possible to arrange the dogs so that initially, at least, the less-acclimated (i.e., non-Davis) dogs were quartered farthest from the open side.

As a result of these precautions, no illness developed in the dog colony, either when first brought to Mercury or when placed in the field array, in spite of occasional exposure to some very wet, raw weather.

Fifty rats for cloud passage (acute) exposures only were obtained from the Atomic Energy Project at the University of California in Los Angeles, courtesy of R. J. Buettner. Packaging and shipping of rats is quite practiced, so no specific problems were involved.

Burros and sheep destined for postshot placement in the field and chronic exposure were procured from local ranches, so acclimatization was unnecessary.

2.2 EXPOSURE CAGES

Several important criteria governed the design of field exposure cages: (a) cages would have to be movable, since of necessity they were to be built in Mercury and transported 55 miles to the test area; (b) relocation in the field might be necessary if the initially selected sites later proved to be incorrect as more definitive isopleths of concentration were drawn; (c) cages should be easy to assemble, since it was planned to erect them at the selected stations under full "rad-safe" conditions; and (d) they must be suitable for the animal and reasonably easy to maintain.

The design ultimately derived is illustrated in Fig. 2.1. The over-all size is roughly 12 feet long, 6 feet wide, and 6 feet high. A divider panel in the middle leads to a 6-foot cube for each animal. The cages are made up of angle-iron frames with 1- x 2-inch mesh, welded-wire panels stitched on with hog rings. The base is a 6- x 12-foot skid made up of 3/4-inch marine plywood and 2- x 6-inch fir runners. Each assembly consisted of seven pieces: two ends, a top, a plain side, a side with two doors, a center divider, and a skid. The steelwork was bolted together and spiked to the skid.

Furniture in the cages included a wine or olive barrel (30-gallon) mounted on chocks for stability, a water bucket, and a sun shade. The barrel provided snug sleeping quarters for the animals during the cold nights experienced at the inception of the experiment, while the sunshade provided protection from the blazing sun but with full freedom for cooling breezes and any attendant airborne contamination.

The final design fulfilled most of the predicated criteria. Transport of the subassemblies from the construction area to the staging area in the field posed no problems. It was found that skidding the complete assembly, or even trains of two or three assemblies, although performed only to a minor extent, was entirely feasible with tactical prime movers, in spite of sagebrush hummocks and other surface irregularities.

A "dry run" in Mercury showed, however, under full protective clothing conditions, that the physical work for assembling the pieces was excessive, so this part of the plan was subsequently modified, as will be detailed in a later section.

Animal comfort was found to be good as far as the dogs were concerned. Because of the double nature of the assemblies and the arrangement of four assemblies per station, these normally gregarious animals were not subjected to loneliness and indeed throve in the fine desert climate. Sheep which were installed in the cages a few weeks after the detonation found them somewhat restrictive, although not seriously so.

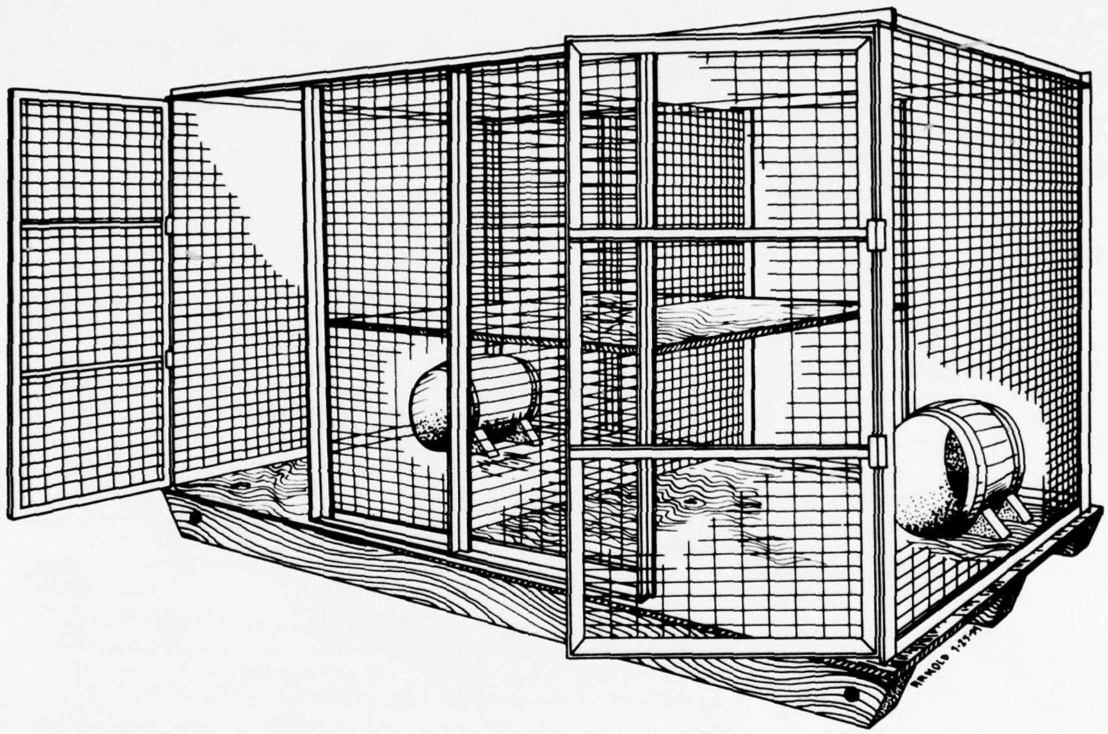

Fig. 2.1—Exposure cage. Skid-mounted, 12- x 6- x 6-foot cages were designed to hold one dog in each half. As shown, each half was furnished with a 30-gallon wine or olive barrel mounted on chocks to provide shelter during adverse weather. In addition a sun shade was provided.

2.3 LABORATORY TRAILERS

Initially, extensive use was made of CETG facilities, but it was recognized that this space would have to be yielded as Operation Plumbbob got under way. By this time most of the animals were already placed in the field, so the only pressing need was laboratory space where the serial autopsies and other laboratory procedures could be performed. This need was easily and fairly comfortably met by modifying two small house trailers (see Fig. 2.2). These were nominal 18-foot trailers (the dimension is measured over the drawbar) which were stripped of all the usual appurtenances. Work counters, shelves, and sinks were installed along one side. An evaporative air cooler was installed in the roof of each. An enclosed breezeway connected the front doors of the two trailers which were parked headed in opposite directions, twelve feet apart. In addition to providing easy communication between the two trailers, this area also served to house a deep freeze, a refrigerator, and an electric water heater.

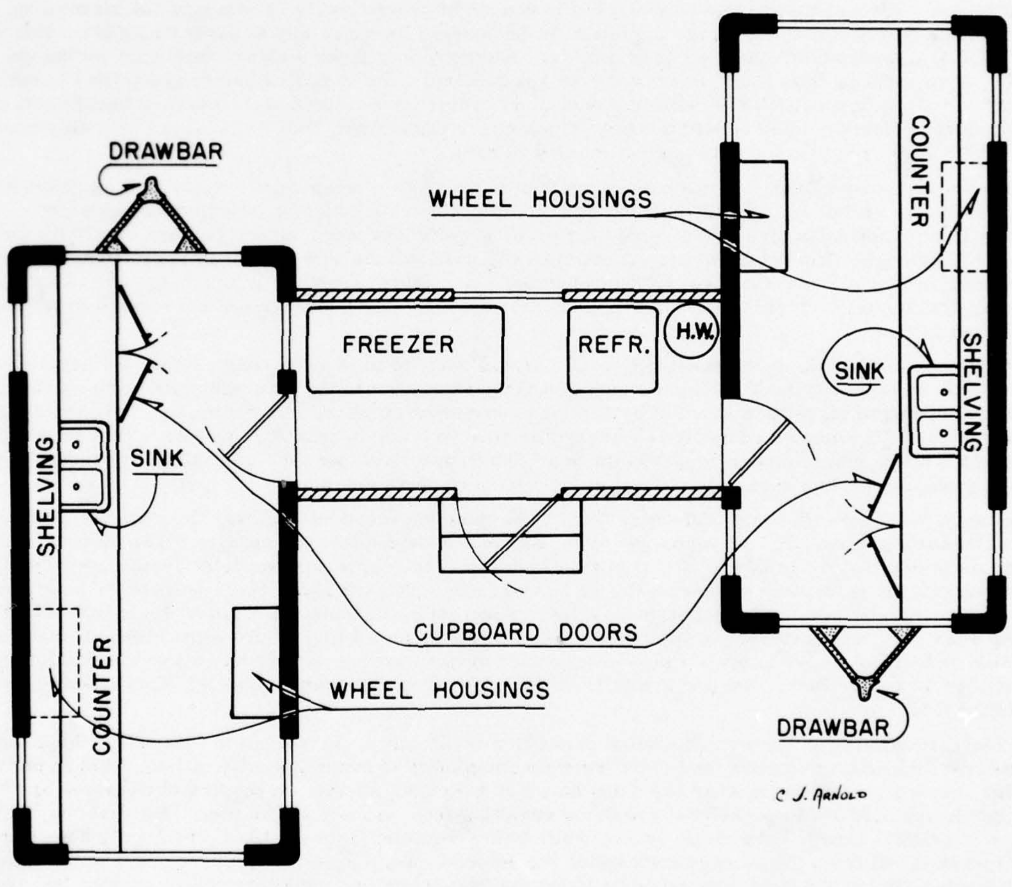

Fig. 2.2—Floor plan of laboratory trailers. These were modified 18-foot house trailers connected by a 12- x 6-foot breezeway.

Water and electric power were supplied to the trailers from the normal test site facilities. Waste water, while not of concern from a sanitation standpoint, had a definite contamination potential, particularly at autopsy times when considerable amounts of water were used in the control of possible cross contamination. Consequently, it was deemed unsatisfactory to dump such waste water on the surface of the ground; a waste

pit, 12 x 12 x 12 feet, was dug and filled with 1/2-inch gravel. With this arrangement, any contaminated water would percolate out of the pit well below the surface, and many miles intervened between the pit and the nearest tap into the aquifer which might bear water originating from this source.

Additional facilities at the trailer site included an 8- x 8- x 8-foot "Brock" house, essentially a movable storage shed, which was used for warehousing materials and supplies such as dog food, Kimpak, etc. A skinning shed was erected near the trailers in order to ensure privacy during this phase of the autopsy procedure.

Living space for control animals was provided by three of the double-cage assemblies described in Section 2.2 which were erected in the vicinity of the trailers. Except for location, therefore, control exposure was essentially the same as field exposure.

2.4 PERSONNEL PROTECTION

Although no firm estimate could be made of the degree of hazard likely to obtain in the target area, it was recognized that it could be severe, particularly at close-in locations and at early times after the detonation. It was also expected that a great deal of very hard physical labor would be required during the placement of cages once the proper locations were established. The radiation safety group for Operation Plumbbob had already specified the minimum personnel protection required until levels of hazard and necessary degree of protection could be established: complete clothing right down to the skin, with all openings taped, and full-face respirators with high-efficiency filters.

From previous experience, it was recognized that high levels of respiratory protection and hard work, while not mutually exclusive, are difficult to obtain. Breathing resistance, particularly across high-efficiency filters, functions directly in opposition to the greatly increased oxygen demand of a hard-working individual. Prolonged effort under these circumstances, particularly with untrained personnel, can actually lead to anoxic collapse and serious physiological strain. A frequent alternative result is poor fitting of the face-piece, intentional or accidental, leading to intolerable face-piece leakage and consequent breathing of contaminated air.

In order to combat this double-ended problem, it was decided to provide field crews with supplied-air respirators.* While not standard items as supplied, they were assembled from standard parts, with special harnesses designed to make them as comfortable and convenient as possible. Each man, then, was fitted with a wide-vision face piece, connected by accordion hose to a low-pressure regulator. This regulator was connected by 75 feet of moderate-pressure hose to a 2-tank manifold through a high-pressure regulator. The tanks were mounted on each side of the field trucks, two pairs per truck.

The tanks used were standard 220-cubic foot, 2200-psi compressed-air tanks, the contents of which were free of carbon monoxide, oil vapor, or other noxious or unpleasant ingredients. The tank regulator reduced this high pressure to 50- to 60-psi hose pressure. The respirator regulator further reduced this pressure so that the face-piece pressure was +2 inches H_2O. Thus all leaks would be outward and no contaminated air could be breathed. Although a further reduction in face-piece pressure would have made breathing even more comfortable, it was felt that the increased possibility of pressure reversal made such a reduction undesirable. With this arrangement, a man at hard work in a well-fitted mask was afforded protection for 12 to 16 hours. Even with a poor fit (e.g., over metal-frame glasses), the air supply was adequate for 6 to 8 hours.

Although considerably more cumbersome than filter respirators, as well as more costly, these supplied-air masks performed as required, and there were no complaints of breathing difficulties. This is not to imply that they were pleasant to wear for many hours at a stretch; as yet, no respiratory devices are. The long supply hoses also led to occasional problems resulting from storage difficulties. Fortunately, this did not occur at critical times, but at least twice, while being returned from the field, the supply hose was ruptured when it fell from the storage rack under the vehicle. A spring-loaded take-up reel would have been preferable, but at the time none could be found that would perform reliably on air, without leakage, for extended periods of time.

With the completion of the heavy work and with the accumulation of information regarding the extent of the hazard in the target area, it was recognized that this degree of respiratory protection was no longer needed, and field personnel were given the option of supplied-air respirators or full-face filter respirators.

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*Scott Aviation Corp., Lancaster, N. Y.

It must be admitted that the latter were chosen chiefly because of the considerably greater convenience in use. With time, restrictions were still further reduced so that ultimately, except within the 100 -μgm/m^2 line, half-face respirators with high-efficiency filters were considered acceptable.

Although compliance with health and safety requirements were under the jurisdiction of Reynolds Electric and Engineering Company (REECO), the supplied-air masks were the sole responsibility of Program 72. However, REECO cooperation, to the extent of supplying air, equipment decontamination, monitoring, etc., was extremely valuable. In all other aspects of radiation safety control, Program 72 made full use of REECO facilities, which included full protective clothing from the ground up, monitoring, and decontamination facilities for personnel, animals, and equipment. Surveillance over the efficacy of respiratory protection was maintained by use of routine nasal swabs.

Much of the success of the field aspects of this operation is directly attributable to the aid and cooperation of REECO Health and Safety personnel who manned the forward decontamination station for many long months, and to Health and Safety supervisory personnel who smoothed the way to an efficient operation without compromising radiation safety standards.*

2.5 OPERATIONAL PLAN

The dog exposure schedule was designed to approximate as nearly as possible the three types of exposure mentioned at the beginning of Chapter II. At shot time, it was planned that there would be 24 dogs in a downwind array at 500, 1000, and 2000 feet from Ground Zero (GZ). (See Fig. 2.3.) On the 500-foot line, cages were placed 200 and 600 feet east and west of the north-south centerline. At 1000 feet one cage was situated on the centerline, while others were located 600 feet east and west. At 200 feet, one cage again was located on the centerline, while additional cages were placed 400 and 800 feet east and west.

These locations were quite arbitrary; the innermost distance was selected as one not likely (chances less than 1:100) to experience flying-missile problems, while the outer distance was selected on a basis of probable maximum cloud concentration. The east-west spread was based on estimates both of variability from a centerline wind direction and of possible cloud width.

The cages were placed completely assembled, with olive barrels for shelters, but without sunshades. It was planned that just before shot time the barrels would be removed so that there would be no possibility of the animals being sheltered from the cloud as it passed. The sunshades were not as readily removable, so it was planned to install them some time subsequent to the detonation. Weather conditions and insolation at the time were such that it was not expected that the dogs would need the protection of the sunshades.

Original experimental design called for chronic exposures at locations where ground-contamination levels were 10, 100, and 1000 μgm/m^2, the intent being to bracket the oft-quoted[5] "safe" level for ground contamination of 100 μgm/m^2 with significantly higher and lower levels. Actual grid locations were to be determined by an evaluation of ground-contamination estimates made by the Monitoring Procedures Group (Program 74) under R. E. Butler, and by an estimate of most probable wind direction for the summer season. Each isopleth was to have three stations, with 8 dogs at each station, for a total of 72 chronic dogs.

The original operations plan called for erection of these cages at selected points in the grid, using 2-1/2-ton tactical cargo trucks, smaller support trucks, and a portable power source for equipment such as drills and electric impact wrenches. By the first ready date, April 10, 1957, all acute exposure cages were in place, and subassemblies for the chronic cages were at the forward "Decon" station. As mentioned previously, a dry run had shown that the physical effort involved was severe, but by April 10 time had not permitted any modification of the original schedule of operations.

The shot-day operational schedule was put into effect, 24 dogs were transported from Mercury to the acute cages, and shortly before H-Hour (the scheduled detonation time) the dog shelters were removed and the rats in wire cages were placed at several of the dog locations, four to a cage, 2-1/2 feet above the ground. These locations were on the 500-foot line at each dog cage, on the 1000-foot line at the centerline cage only, on the 2000-foot line at the centerline cage, and at each of the end cages on this line.

Expected slackening of the wind did not materialize, however, and the test was postponed. Following postponement, the rats were recovered and the barrels were replaced in the dog cages. In view of the uncertainties relative to the next possible shot day, it was decided to leave the acute dogs in the field. This had the added benefit of giving the field crews experience in caring for the dogs in the exposure cages.

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*Particular appreciation is due William Johnson, head of Health and Safety Division, and Wesley Wilcox, head of the Radiation Safety section, REECO, in this area.

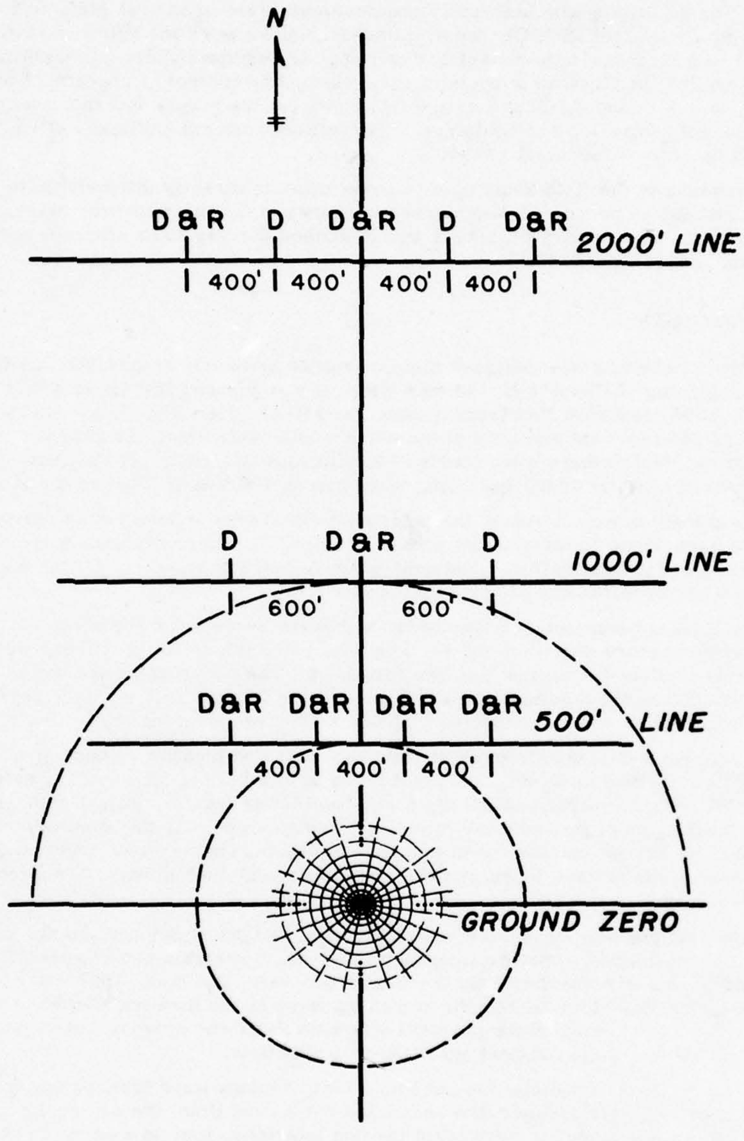

Fig. 2.3—Layout of cloud passage (acute) array. Locations marked "D" only were dog stations. Those marked "D & R" had both dogs and rats present at *time of release*. Not shown are balloon rat locations which were on 500-foot circle, due north and 15 degrees west of north.

Since it had already been demonstrated that assembly of the exposure cages under "rad-safe" conditions was unduly difficult, the original operations plan was modified at this time to the extent of allowing pre-assembly of the cages just inside the demarcation line between "clean" and "contaminated" areas at the Decon station. It was proposed that the heavy trucks (one of which was outfitted with a hoist and monorail) would be used to haul the fully assembled cages to the grid points.

This plan would necessitate a great deal more driving, since, at most, only four assemblies could be carried at one time, and of course artificial resuspension of deposited contamination was most undesirable; it was felt, however, that driving at moderate speeds over well-established routes would not result in serious amounts of resuspended dust, even from heavy ten-wheelers. There was no doubt that this procedure for locating the cages would prove much easier on personnel. Consequently, the time between April 10 and the actual shot day, April 24, was spent, in part, preparing for and trying out this mode of operation, which, in the practice runs, proved quite satisfactory.

By April 23 (D minus 1), Program 72 was thoroughly organized. A "damp" run on April 17, which resulted when a second attempt to detonate the shot was foiled by precipitation, had helped to iron out most of the operational difficulties associated with the acute experiment. About two hours before shot time on April 24, the barrels were removed from the dog cages, rats were placed as before, and an additional group of rats was flown in the Particle Physics Group (Program 71) balloon array. It was intended that four strings of rats be flown, three rats to a string, on balloon cables 500 feet from ground zero, 15 degrees west of north (345 degrees), and due north (360 degrees). One string on each cable was to have rats at 900, 700, and 400 feet above terrain, and the other was to have them at 500, 300, and 100 feet. At alternate 100-foot intervals Program 71 had wind-powered electrostatic precipitators.

In practice, the balloon array was not quite as contemplated. Difficulties were experienced in raising the strings to the specified elevations, and the upper string of rats on the 345-degree cable was lost when the connection at the balloon cable failed. It is estimated, however, that the nine remaining rats were within 50 feet of the desired elevation.

The detonation occurred at 0627, April 24, 1957.

As soon as monitoring teams had confirmed the expected absence of beta-gamma activity in the vicinity of the detonation point, acute animal recovery was initiated. All animals were found alive with no evidence of missile injury, and all animals for the "cloud-passage-only" phase of the experiment were recovered. This group consisted of all rats, one far-east and one far-west dog from the 500-foot line, one centerline dog from the 1000-foot line, all of the far-east and far-west dogs, and one centerline dog at 2000 feet.

These animals were transported back to the decontamination area where a second crew, properly suited, immediately instituted animal decontamination by first using vacuum cleaners on the animals and then bathing them in warm sudsy water. When dry, these animals were passed by Health and Safety personnel, transferred to uncontaminated containers in clean vehicles, and transported 55 miles back to the autopsy trailers in Mercury.*

For several reasons, placement of the chronic exposure cages was delayed until April 26 (D plus 2). Chief among these was a desire to obtain the best possible determination, under field conditions at least, of the locus of the desired isopleths. A tremendous amount of data had to be accumulated and evaluated to make this determination, and it is a real tribute to Program 74 that only two days were required to accomplish it.

Cages were located at numbered grid points on the grid layout established by Sandia. GZ was at 2535. The first two digits (25) denote the north-south coordinate; the second two digits (35) denote the east-west coordinate. Distances and directions from GZ are readily ascertained by examination of Fig. 2.4 which shows cage locations. Cages were placed at grid points 2735, 2736, and 2636 on the 1000-μgm line; on the 100-μgm line, cages were at points 3539, 3341, and 3143; and on the 10-μgm line they were located at points 5251, 5448, and 5645.

It will be noted that these stations are in a generally northeasterly direction from GZ. This direction was selected on the basis of meteorological advice as the most probable wind direction for this valley for the summer months.

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*In accordance with previous planning, mongrel dogs obtained from the pound were ordinarily used for earlier studies, the genetically more homogeneous beagles for longer-term studies.

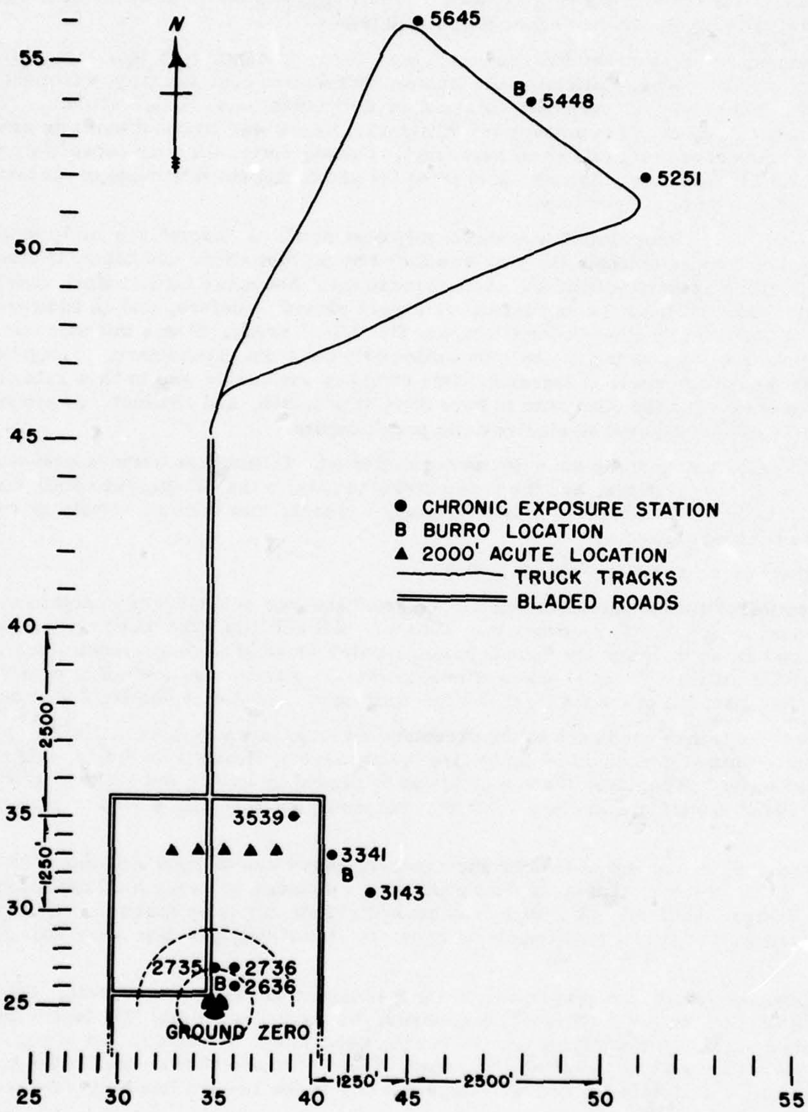

Fig. 2.4—Layout of chronic array. The 2000-foot acute locations are also indicated for orientation purposes.

Soil sampling, followed by chemical analysis, showed that the ground levels were actually 560, 40, and 2.6 $\mu gm/m^2$, instead of 1000, 100, and 10 $\mu gm/m^2$. These values were not obtained, however, until a considerable time had elapsed, and it was decided not to move the cages.

On D plus 2, cage placement was initiated, with completion on D plus 4. In order further to save time and effort in the placement operation, a minor procedural modification was made, in that an additional crane truck was employed to load the cages onto the contaminated vehicles. This truck had a power-operated hoist which was considerably faster and, of course, far less strenuous for personnel than was the hand-operated chain fall on the monorail truck. It is probably fair to say that the better part of one day was saved in the placement operation as a result of this assistance.

Also on D plus 2, the combined acute and chronic exposure study was initiated with the sacrifice of four dogs which had been in the cloud. Two of these were from the 500-foot line, 200 feet each side of the centerline, one was from the 1000-foot line on the centerline, and the fourth was from the 2000-foot line, also on the centerline.

Placement of the chronic animals occurred on April 29 (D plus 5), with all dogs being installed the same day. Three burros (all jennies) were placed on each isopleth at the same time in an attempt to evaluate, at least to a minor extent, the hazard to grazing animals under such circumstances.

With completion of animal placement, the operation slipped into a routine that was to last for approximately 160 days, broken only by Plumbbob detonations and serial sacrifices. The schedule for the latter called for removal of two animals from each isopleth 4, 8, 16, 32, 64, 96, and 128 days after placement, and four from each isopleth 160 days after placement. A total of 72 dogs was included in the initial chronic animal placement, 24 per isopleth. This number provided 18 experimental dogs and 6 spares, the latter for use as replacements in case any of the experimentals should be lost for unforeseen reasons. The sacrifice schedule for individual animals is shown in Tables 3.1 through 3.4, Chapter 3.

Additional animals were placed in the field 32 days after the first placement day. These included three sheep on the 1000-$\mu gm/m^2$ line, three sheep and four dogs on the 100-$\mu gm/m^2$ line, and three sheep on the 10-$\mu gm/m^2$ line. These animals were sacrificed 128 days after placement, at the same time as were the 160-day chronic animals from the initial group.

2.6 ROUTINE ANIMAL CARE

Care of animals in the field soon settled down to a fairly normal, routine procedure. The military personnel were split into two crews working alternating schedules, so arranged that no individual had more than two consecutive days in the field, and each had two consecutive days off at least every two weeks. This leniency was found to be vitally important in sustaining morale and enthusiasm in an inherently unpleasant job.

Food for the dogs was Kasco Meal, moistened to a firm pudding consistency with a soup made of Ken-L-Ration and hot water, at the rate of one pound of Ken-L-Ration for each ten pounds of meal. Although Kasco alone is considered an adequate diet, the admixture of Ken-L-Ration further increases the acceptability of the meal. This was particularly important in the early stages of the operation when the dogs were in strange surroundings and under somewhat trying conditions.

Dog food was stored and mixed at Mercury, and transported to the field in 10-gallon covered cans. Water was available at the decon station, hauled there by tanker, for showers and vehicle decontamination. Hay for the burros and sheep was also stored at this station.

At the decon station the field crew was further divided, one half taking care of the three stations on the 10-$\mu gm/m^2$ line, the other half servicing all other stations. This apparent inequity in effort was more than balanced by the long-distance travel over nearly impassable trails required for attendance of the outer stations.

After "suiting up", each subteam loaded already contaminated trucks with dog food, hay, and water, and proceeded to their assigned work places. The cages were shovelled clean, sluiced with whatever water remained in the buckets in each cage (extra water was carried in case there was insufficient water remaining), fresh water was supplied, and the animals fed. With the burros, sluicing was of course without meaning; but watering tubs were dumped each day and filled with fresh water. At fairly frequent intervals, all animals were inspected by one of the veterinarians; but the only finding was a tendency towards obesity in the dogs, which led to a reduction in the ration.

During the first month of exposure in the field, two or three dogs showed a transient mild diarrhea lasting about 48 hours. There was no impairment of appetite and they recovered without medication. There was no respiratory infection at any time. The dogs were in robust good health and, with allowance for a half dozen of quiet temperament, remained in high spirits through the entire confinement.

The burros and sheep maintained good health during exposure and gained weight.

This routine was occasionally interrupted by two factors. One of these was the autopsy schedule, detailed in another section. The other was the rest of the Plumbbob series. Not infrequently, test detonation in this series would seal off access to Area 13 because of high radiation fields. Two approaches were essayed to solve this problem. One of these was the use of alternate routes. The Nevada Test Site is crisscrossed with roads, and aerial photos show many alternate routes from one point to another. What the photos do not show, however, is that most of these roads are nearly or actually impassable, even with all-wheel-drive vehicles. As a consequence, alternate routes were in most cases unfeasible. A particular problem in this regard was the sometimes incomplete definition of the fallout isopleths, whereby an attempted alternate route might suddenly show unacceptably high radiation fields. The alternate off-site route, through Las Vegas, Glendale, and Alamo, involved 500 miles of driving and was considered impractical.

The second approach was the use of helicopter support, with field crews and their supplies being airlifted directly from Mercury to a landing strip in the vicinity of the decon station. This approach eliminated radiation problems enroute but was not always available, since, on certain shots, all helicopters were assigned to operations associated with the shot. As a result, on a few occasions, it was necessary to omit animal care for a day. On one such day, radiation levels in the area were too high for prolonged occupancy, even had crews been able to reach the area. Some stations received doses as high as 14 r (cumulative 30-day dose).

2.7 AUTOPSY PROCEDURES

In order to determine the extent of plutonium uptake in the experimental animals, these were removed from the field after varying exposures (outlined in Section 2.5), decontaminated at the decon station as thoroughly as possible by washing and vacuuming techniques, passed by Rad-Safe personnel as having less than 500 dpm over the area of the probe, transferred to clean boxes in clean vehicles, and transported back to the laboratory trailers in Mercury. Here the dogs were killed with Lethol, Euthanol, or Nembutal, and the carcasses were bled out as thorougnly as possible and skinned. The latter step was a further attempt to minimize contamination of the tissue samples, since it was recognized that, in spite of the utmost care in decontamination and careful monitoring of the cleaned animals, there was a high probability of residual, undetectable fur contamination. The skinning procedure and a subsequent washing of the carcass with clear water served to prevent introduction into the carcass of plutonium which was, in truth, purely superficial in nature.

The carcasses were then dissected and tissues taken for plutonium analysis. These included lung, liver, trachea, spleen, gastrointestinal tract, femur, rib, nasal mucosa, and hilar and mediastinal lymph nodes. In most cases, the whole organ was taken, weighed, a small sample removed for autoradiography, and then sealed in a polyethylene bag. Ribs and femurs were exceptions in that only a single rib or femur was taken for analysis; another rib and the other femur were prepared for autoradiography.

At autopsy, no gross lesions were seen which might have been indicative of pathology arising from radiation or other causes. Two or three dogs showed a few roundworms in the gut (ascarids) but there was no indication that the dogs' condition was affected by this infestation. Subcutaneous and visceral fat was abundant.

Burro and sheep autopsies were performed in the field in the vicinity of the decon station with as much care as possible being taken to avoid cross-contamination. Tissues taken included lung, hilar lymph node, and rib. Two of the burros, found to be pregnant, were estimated to be between the second and third trimester of pregnancy. (One burro delivered a normal, healthy foal some months prior to autopsy.) Fetal tissues were saved for analysis.

Throughout the dissections, efforts were made to avoid cross-contamination of the tissues, but it cannot be stated positively that there was <u>no</u> transfer of activity. This problem was particularly acute with the early high-level dogs, some of which had tens of thousands of disintegrations per minute in the total body. Among the procedures used to control contamination during dissection were frequent changes of scalpel blades, particularly after removal of tissues suspected of containing relatively large amounts of activity, and meticulous scrubbing of instruments after use with "Joy" and citric acid.

All material not needed for analysis (blood, pelt, carcass remains) were packaged in Kimpak and placed in 10-gallon trash cans, the covers of which were then wired shut to prevent molestation by coyotes or big cats. The cans were taken out by the feeding crews the following day for disposal in the burial pit near the decon station.

The collected tissues were stored in the deep freeze until enough were accumulated to make a shipment, at which time they were packed in dry ice and flown to Albuquerque for analysis by Sandia.[6]

Chapter 3

BIOMEDICAL PROGRAM RESULTS

In hazard evaluation of the type required of Test Group 57, the experimentation involves both physical and biological measurements. Physical measurements are designed to characterize the atmospheric contamination in terms of particle size, air concentration, and chemical properties of the aerosol, and to integrate these with prevailing weather conditions. The biological counterpart is designed to determine what fraction of the aerosol presented to an animal is deposited in the lung, what fraction of this remains, how long it remains, and what fraction that enters the body deposits in the so-called critical organ or organs. In the case of plutonium oxide, which is presumed insoluble in body fluids, the National Committee on Radiation Protection assumes that lung would be the critical organ. For soluble plutonium, the skeleton is considered critical.

3.1 BIOMEDICAL PROGRAM DATA

Biological experimentation under well-controlled conditions in the laboratory, in general, produces data which follow some type of distribution which will permit statistical analysis by established methodology. Plutonium concentrations in tissues obtained in Program 72, however, were very low, and because exposure conditions (wind, weather, precipitation, etc.) were uncontrollable in the field, most of the data were not suitable for analysis by usual statistical means. However, it is possible to apply a log normal distribution analysis to some of the "acute" tissue data as shown by Merritt et al.[7] Such an analysis enables one to make important statistical statements, but this type of distribution is a difficult one to interpret biologically. The erratic nature of the tissue distribution data with time of sacrifice may be seen in Tables 3.1 through 3.4. A quick comparison of the "acute" with the "chronic" tissue analysis will point out the higher numbers in the former tissues. The fact that the acute data are higher and that they also follow a statistical distribution may be quite significant, and this point is discussed in more detail later. Had the numbers been comparable in the chronic animals they, too, might have been log normal in distribution. The only tissue which shows an obvious trend with time is the gastrointestinal tract plus contents, the activity of which decreases with time, but this is no doubt due to plutonium in the contents.

Merritt's analysis of the acute exposure data is extremely helpful but, since the chronic data will not submit to standard statistical techniques, and in order to compare the two specific exposure cases, it seems advisable to treat them as if exposure time were not a factor for consideration (except for GI tract), and to use the median value for any tissue to represent its plutonium concentration at a given location without regard to time of sacrifice.* The median is particularly recommended for hazards analysis since, even though greater numbers of dogs might be exposed, the median would be expected to change very little, while the highest single value obtained for any tissue could increase greatly. The decrease with time of values for GI tract plus contents is an exception to this, but since these dogs were free to lick their fur and the surroundings, the GI tract burden is without meaning in comparison with what man would accumulate under similar exposure circumstances. This point is covered in more detail in another section.

While there is very slight indication that lung decreases with time of sacrifice at the 500- and 1000-foot locations, the opposite pattern is seen at 2000 feet. Because these trends are so insignificant and in opposite directions, all acute and acute-chronic lung values will be treated as one population. Use of the median, however, simplifies comparison of tissues for the GI tract. This could be somewhat in error as far as

*The basic reason for using the median instead of the mean is that an extremely high value can cause the mean to be above the next highest number and might lead to an error in interpretation. This would be the case, for example, with the plutonium concentration in liver as presented in Table 3.3.

TABLE 3.1—PLUTONIUM CONCENTRATION IN TISSUES OF CHRONIC DOGS AND BURROS ON 10-μgm/m^2 ISOLEVEL LINE

Dogs

Time of sacrifice	Location	Radioactivity in disintegrations per minute per gram									
		Spleen	GI tract*	Liver	Hilar LN	Med. LN	Lung	Trachea	Nas. nuc.	Femur	Rib
P + 4	54, 48			0.001	0	10.000	0.255	0	0.333	0.086	0.098
P + 4	56, 45	0	0.660	0	0	2.500	0 (sp)	0.082	0.146	0.198	0.769
P + 8	56, 45	0	1.509	0.013	9.524	4.167	0.043	0.073	0	0.201	0.333
P + 8	52, 51	0.058	0.207	0.006	1.333	15.000	0.231	0.066	1.429	0.053	0.508
P + 16	52, 51	0.017	0.550		0	5.000	0.066 (sp)	0	0.485	0.061	0.114
P + 16	54, 48	0.038	0.008	0.354	7.500	0.333	0.006	0.148	0.556	0.436	0.127
P + 32	56, 45	0.022	2.212	0.015	0.750	3.333	0.032	0.018	0	0.638	0.111
P + 32	52, 51	0	0	0.005	67.000	920.454	0	1.322	0	4.754	
P + 64	56, 45	0	0.095 (sp)	0.001	41.379	0	0.521	0	4.787	0.198	5.357
P + 64	52, 51	0	1.328	0.004	0.060	0	12.208	0.230	0	0.069	0
P + 96	52, 51	0	0.576	0.021	8.400	115.000	0.069	0.044	0	0.045	0.719
P + 96	56, 45	0.023	0.070	0.010	5.333	0.667	0.086	0.228	0.818	0.016	0.088
P + 128	52, 51		0.693		5.000	40.000	0.178	0.055	1.500	0.163	0.127
P + 128	56, 45	0	0.077	0		3.333	0	0	1.000	0	0.082
P + 160	54, 48	0	0.258	0.007		3.200	0	0.041	0.086	0.064	0.636
P + 160	52, 51	0.056	0.027	0	2.000	10.000	0	0		0.116	0.237
P + 160	56, 45	0.202	0.030	0.003		6.667	0.455	0	3.385	0.102	
P + 160	54, 48	0	0.123	0.002	1.951	1.923	0.009	0	0.116	0.956	0.250

*Intestinal contents included

Burros

Time of sacrifice	Location	Radioactivity in disintegrations per minute per gram		
		Lung	Hilar LN	Rib
P + 160	54, 48	0.007	0.654	0.046
P + 160	54, 48	0.020	0.145	0.176
P + 160	54, 48	0.292	6.364	0.491

TABLE 3.2—PLUTONIUM CONCENTRATION IN TISSUES OF CHRONIC DOGS AND BURROS ON 100-μgm/m^2 ISOLEVEL LINE

Dogs

Time of sacrifice	Location	Radioactivity in disintegrations per minute per gram: Spleen	GI tract*	Liver	Hilar LN	Med. LN	Lung	Trachea	Nas. muc.	Femur	Rib
P + 4	33, 41	0.039	0.812	0.045	0	2.632	0	0.076	0.235	0.022	1.724
P + 4	31, 42		4.551	0.014	0	4.00	0.146	0	0	0.042	0.132
P + 8	35, 39	0.103		0.007	0	8.966	0.015	0.041	0.182	0.133	0.385
P + 8	35, 39	0.186	2.104	0	10.0	5.20	0.027	0.386	0.636	0.037	0.816
P + 16	33, 41		0.579	0.006	4.651	1.194	0.055	0.029	0.835	0.265	0.645
P + 16	33, 41	0	4.542	0	12.727	22.083	0.926	0.274	0	0.025	0
P + 32	31, 42	2.745	1.635	0.101	28.571	280.0	0	1.810	20.909	0.886	12.200
P + 32	35, 39		3.334	0.005	15.00	9.091	0	0.048	0.661	0.010	
P + 64	35, 39	0		0.014		17.857	0.078	1.058	0.457	0.093	0.833
P + 64	35, 39	0.517	0.012	0.015	0	0	0.007	0.348	0.769	0.044	41.552
P + 96	33, 41	0.021	Lost	Lost	16.364	12.000	0.019	0.096	0.027	0.067	0.400
P + 96	33, 41	0.098	0.338	0.0006	21.500	3.500	0.039	0.142	0.500	0	1.208
P + 128	35, 39	0.031		0	2.667	10.00	0.270	0.100	8.333	0.137	0.211
P + 128	33, 41	0.031		0.004	2.162	12.500	0.034		1.347	1.312	0.542
P + 160	35, 39	0	1.141	0.009	2.00	7.500	0.534	0	0.909	0.043	0.455
P + 160	31, 42	0.047	0.145	0.007	0	4.00	0	0.513	2.222	0.053	0.161
P + 160	31, 42	0	6.226	0.005	13.333		0.168	0.208	0	0.095	0
P + 160	31, 42	0	2.538	0.017	53.846		0.314	0	2.632		0.476

*Intestinal contents included

Burros

Time of sacrifice	Location	Radioactivity in disintegrations per minute per gram: Lung	Hilar LN	Rib	Fetus
P + 160	33, 41	0.061	0.500	0.013	
P + 160	33, 41	0.026	0.778	0.147	
P + 160	33, 41	0.032	0.526	0.255	0.219

TABLE 3.3—PLUTONIUM CONCENTRATION IN TISSUES OF CHRONIC DOGS AND BURROS ON 1000-μgm/m^2 ISOLEVEL LINE

Dogs

Time of sacrifice	Location	Radioactivity in disintegrations per minute per gram: Spleen	GI tract*	Liver	Hilar LN	Med. LN	Lung	Trachea	Nas. muc.	Femur	Rib
P + 4	27, 35		20.494	0.069	5.333	3.488	0.265	0.862	0.345	0.032	0.424
P + 4	26, 36	0.088	Lost	Lost		7.000	0.308	0	0.583	0.059	0
P + 8	27, 36	0	101.972	0.074		1.667	0.564	0.228	0.327	0.091	0.256
P + 8	26, 36	0.058	49.256	0.007	2.667	10.000	0.687	0.185	0.875	0.058	7.895
P + 16	27, 35	7.469		0.002	1.750	0		1.809	0	0.033	0.049
P + 16	26, 36	0.035	15.115	0.006	0	8.667	0.353	0.495	0.385	0	1.099
P + 32	26, 36	0	5.080	0.011	1.694	2.899	0.017	1.918	1.409	0.093	1.111
P + 32	27, 35	0.035	Lost	0.018	6.274	32.963	0.576	0	0	0.239	0.346
P + 64	27, 36	0	55.213	0	5.714	7.500	0.618	0	0.444	0.049	0.500
P + 64	27, 35	0.127	0.009	0	14.211	0		0	1.055	0.050	0.700
P + 96	27, 35	0	0.006	0	3.590	4.444	0.766	0	0.051	0.084	0.529
P + 96	27, 35	0	Lost	130.655	1.053	0		0.257	0.270	0.120	0.667
P + 128	27, 36	0	3.673		2.222	4.706	0.695	0.151	0	0.013	0.938
P + 128	26, 36	0		0.008	20.000	0	0.609	0.048	0.097	0.070	0.968
P + 160	26, 36	0	1.732	0.015	5.333		0.427	0.054	0.909	0.074	
P + 160	27, 36	0	2.711	0.009		41.667	1.915	0	0.478	0.043	1.136
P + 160	27, 36	1.677	3.061	0.015	4.000	10.526	0.341	0	0.094	0.114	0.870
P + 160	26, 36	0	0.476	0.027	0	20.833	1.986	0.165	0.307	0.051	0

*Intestinal contents included

Burros

Time of sacrifice	Location	Radioactivity in disintegrations per minute per gram: Lung	Hilar LN	Rib	Fetus
P + 160	27, 36	0.089	0.435	0.083	0.027
P + 160	27, 36	0.472	0.615	0.047	
P + 160	27, 36	0.154	1.154	0.096	

TABLE 3.4—PLUTONIUM CONCENTRATION IN TISSUES OF ACUTE DOGS AND RATS EXPOSED TO THE CLOUD, AND OF ACUTE DOGS REMAINING IN FIELD AFTER CLOUD PASSAGE

Dogs

Time of sacrifice	Distance from GZ	Location	Radioactivity in disintegrations per minute per gram: Spleen	GI tract*	Liver	Hilar LN	Med. LN	Lung	Trachea	Nas. muc.	Femur	Rib
H + 4	500 ft	FW	0.210	7.928		15.000	3.488	0.674		0.911	0.150	0.882
H + 4		FE	5.412	35.659	0.108	0	20.000	1.770			2.277	0.130
D + 2		NW	0	162.502	0	1.449	1.316	0.507	2.016	3.370	0.008	0.120
D + 2		NE		0	0.223	3.333	8.696	0	0.393	73.750	0.272	1.250
D + 9		FW	0	2.025	0.022	4.706		0.966	0.034	2.471	0.244	0.556
D + 11		NW	0	3.361	0.025	1.857	7.778	0.560	0	0.518	0.188	0.577
D + 12		NE	0.177	5.633	0.004	18.182	400.000	0.803	0.482	0.342		0
D + 21		FE	0	8.049	0.009	1.458	2.381	0.019	3.380	0.230	0.012	0.962
H + 4	1000 ft	C	0	140.783	0.009	2.000	23.333	2.101	0.242	4.250	0.022	0
D + 2		C	0	123,800	0	0.673	2.885	8.078	19.186	8.000	0.006	0.789
D + 13		FE	0	7.670	0.433	1.786	2.381	0.242	0.051	0	0.121	0.833
D + 21		FW	0.014	0.0007		0	33.500	0	0.169	8.125	0.062	
H + 4	2000 ft	FW	0	64.024	0.010	8.974	0	0.642	0.054	10.345	0.037	0.591
H + 4		FW	0.530	21.824	0.033	0	0.851	0.494	0.092	0	0.053	0.690
H + 4		FE	0.068	187.184	0.003	20.202	8.081	1.988	0.545	1.133	0	
H + 4		C	0		0.007			0.424	0.030	1.917	0	0.342
H + 4		FE		192.035	0.009	50.000	5.263	0.488	0.111	14.936	0.051	0.250
D + 2		C		62.701	0.025	4.355	8.889	2.816	0.265	20.930	0.102	1.304
D + 8		NE	0.165	29.885	4.884		2.000	6.709	4.855	43.750	0.919	0.250
D + 13		NW	0.107	1.611	0	2.667	80.000	2.003	0.057	0	0.058	0.113
D + 36		NW	0	28.904	0.010	0		0.774	0.179	1.273	0.038	
D + 36		NE	0	0.501	0.007	5.000	3.000	2.963	0	0	0	0

*Intestinal contents included

Rats
(All sacrificed at H + 2 to H + 4 hours)

Distance from GZ	Location	Disintegrations per minute per gram per lung: Rat 1	Rat 2	Rat 3	Rat 4
500 ft	FW	0	28.571	0.663	10.656
	NW	8.805	0	0.838	0
	NE	25.568	3.507	0.452	0.301
	FE	0		13.208	0.746
1000 ft	C	0	0	1.130	2.432
2000 ft	FW	0	0.660	1.705	194.000
	C	0	2.347	17.225	0
	FE	1.258	0		

representing the true concentration at any time. Table 3.5 presents the mean and median tissue weights for all animals sacrificed, but individual tissue weights were used to obtain data on a per-gram basis.

Table 3.6 summarizes Tables 3.1 through 3.4 by presenting tissue distribution data as median disintegration/minute/gram (dpm/gm) for dog and burro as a function of exposure condition.* The decrease in plutonium content of GI tract plus contents and lung with decreasing exposure condition is obvious for dog lung and burro lung. Lymph node concentration remains nearly constant regardless of the exposure level. Dog femur and rib fall into opposite patterns, while burro rib is similar to dog femur. These trends are extremely puzzling, and are difficult to interpret on any known physiological basis.

Table 3.7 presents data in a similar manner for animals placed in the field at P plus 32 days. Here, sheep lungs show the same tendency to decrease with ground contamination observed in the dog data of Table 3.6, and again the lymph nodes remain relatively constant. However, the rib shows neither of the patterns seen with the dog and burro. There is a dip in rib plutonium concentration on the 100-μgm/m^2 line, while values for the 1000- and 10-μgm/m^2 lines are about the same. The dogs placed at P plus 32 show lung and rib values which do not differ greatly from those placed on P-Day (Table 3.6), but the hilar lymph nodes are a factor of two higher.

Table 3.8 presents both acute and chronic data for the GI tract plus contents and for the lung as median dpm/organ. Although it may not be correct to use the median to represent these two organs for all animals in the acute (cloud and cloud-plus-chronic) experiment, the table does indicate that plutonium levels in these organs are higher at 1000 and 2000 feet from ground zero than they are at 500 feet. The summary of chronic data given in this table is a definite indication of the greater lung concentrations by factors of 4 to 15 on the 1000-μgm/m^2 level, even with sheep placed at P plus 32.

Another important purpose in presenting the data of Table 3.8 is to point out the extremely high GI tract-to-lung ratios. These are 10 to 100 times higher than values currently used for dosage calculations by the National Committee on Radiation Protection.[8] The ratios shown here range from 45 to 760, and can be explained circumstantially by the freedom the dogs had to lick their coats and surroundings. In recent field tests for the Aircraft Nuclear Propulsion Program it was discovered that the GI tract-to-lung ratio could be reduced from as high as 20 to values which were less than 1 when the dogs were muzzled.[9] The animals in these latter tests were sacrificed 15 to 45 minutes postrelease instead of 4 hours after removal from the field as in this experiment. These findings indicate that the high GI tract values are not physiologically comparable to those in man, and therefore should not play an important role in dosage calculations.

The implications of Tables 3.6 through 3.8 may be summarized thus:

(a) For the acute animals, lung and GI tract plus contents show a considerable variation (factors of 2 to 25) in tissue plutonium content with distance from ground zero at the time of cloud passage. The GI tract content also varies with time of sacrifice.

(b) With the exception of the GI tract and its contents, the lymph nodes and rib have the highest plutonium concentration on a per-gram basis of any of the organs analyzed. The lymph node concentrations remain relatively constant, while bone values are much more variable.

(c) Most lungs from chronically exposed animals have less plutonium per gram than the foregoing organs.

(d) Animals placed at P plus 32 days in the chronic experiment showed tissue concentrations not greatly different from those animals which were placed on P-Day.

(e) At this juncture, the order of tissue plutonium concentration appears to be (1) the GI tract plus contents, (2) the lymph nodes, and (3) the lung or rib (depending on location).

3.2 DOSAGE CALCULATIONS

To make hazard estimations from an experiment of this nature one should calculate the doses to various organs and compare these to maximum permissible doses established for the case in question (i.e., emergency permissible levels). Radiation dose rates have been calculated for dog and burro tissues in rem per week and are presented in Table 3.9. These are calculated from the median values presented in previous tables for the acute and the 1000-, 100-, and 10-μgm/m^2 lines. An RBE of 10 was used to change rep to rem, and a factor of 5 for "uneven bone distribution" was employed.[8] The exposure period used to obtain a dose rate was the

*It is again emphasized that time of sacrifice is considered a constant for purposes of these comparisons.

representing the true concentration at any time. Table 3.5 presents the mean and median tissue weights for all animals sacrificed, but individual tissue weights were used to obtain data on a per-gram basis.

Table 3.6 summarizes Tables 3.1 through 3.4 by presenting tissue distribution data as median disintegration/minute/gram (dpm/gm) for dog and burro as a function of exposure condition.* The decrease in plutonium content of GI tract plus contents and lung with decreasing exposure condition is obvious for dog lung and burro lung. Lymph node concentration remains nearly constant regardless of the exposure level. Dog femur and rib fall into opposite patterns, while burro rib is similar to dog femur. These trends are extremely puzzling, and are difficult to interpret on any known physiological basis.

Table 3.7 presents data in a similar manner for animals placed in the field at P plus 32 days. Here, sheep lungs show the same tendency to decrease with ground contamination observed in the dog data of Table 3.6, and again the lymph nodes remain relatively constant. However, the rib shows neither of the patterns seen with the dog and burro. There is a dip in rib plutonium concentration on the 100-$\mu gm/m^2$ line, while values for the 1000- and 10-$\mu gm/m^2$ lines are about the same. The dogs placed at P plus 32 show lung and rib values which do not differ greatly from those placed on P-Day (Table 3.6), but the hilar lymph nodes are a factor of two higher.

Table 3.8 presents both acute and chronic data for the GI tract plus contents and for the lung as median dpm/organ. Although it may not be correct to use the median to represent these two organs for all animals in the acute (cloud and cloud-plus-chronic) experiment, the table does indicate that plutonium levels in these organs are higher at 1000 and 2000 feet from ground zero than they are at 500 feet. The summary of chronic data given in this table is a definite indication of the greater lung concentrations by factors of 4 to 15 on the 1000-$\mu gm/m^2$ level, even with sheep placed at P plus 32.

Another important purpose in presenting the data of Table 3.8 is to point out the extremely high GI tract-to-lung ratios. These are 10 to 100 times higher than values currently used for dosage calculations by the National Committee on Radiation Protection.[8] The ratios shown here range from 45 to 760, and can be explained circumstantially by the freedom the dogs had to lick their coats and surroundings. In recent field tests for the Aircraft Nuclear Propulsion Program it was discovered that the GI tract-to-lung ratio could be reduced from as high as 20 to values which were less than 1 when the dogs were muzzled.[9] The animals in these latter tests were sacrificed 15 to 45 minutes postrelease instead of 4 hours after removal from the field as in this experiment. These findings indicate that the high GI tract values are not physiologically comparable to those in man, and therefore should not play an important role in dosage calculations.

The implications of Tables 3.6 through 3.8 may be summarized thus:

(a) For the acute animals, lung and GI tract plus contents show a considerable variation (factors of 2 to 25) in tissue plutonium content with distance from ground zero at the time of cloud passage. The GI tract content also varies with time of sacrifice.

(b) With the exception of the GI tract and its contents, the lymph nodes and rib have the highest plutonium concentration on a per-gram basis of any of the organs analyzed. The lymph node concentrations remain relatively constant, while bone values are much more variable.

(c) Most lungs from chronically exposed animals have less plutonium per gram than the foregoing organs.

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(e) At this juncture, the order of tissue plutonium concentration appears to be (1) the GI tract plus contents, (2) the lymph nodes, and (3) the lung or rib (depending on location).

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To make hazard estimations from an experiment of this nature one should calculate the doses to various organs and compare these to maximum permissible doses extablished for the case in question (i.e., emergency permissible levels). Radiation dose rates have been calculated for dog and burro tissues in rem per week and are presented in Table 3.9. These are calculated from the median values presented in previous tables for the acute and the 1000-, 100-, and 10-$\mu gm/m^2$ lines. An RBE of 10 was used to change rep to rem, and a factor of 5 for "uneven bone distribution" was employed.[8] The exposure period used to obtain a dose rate was the

*It is again emphasized that time of sacrifice is considered a constant for purposes of these comparisons.

TABLE 3.5—MEAN AND MEDIAN TISSUE WEIGHTS OF ALL ANIMALS SACRIFICED IN PROGRAM 72

Tissue	Mean weight (grams)	Median weight (grams)
	Dog	
Spleen	23.9	23.1
GI tract plus contents	548.6	524.3
Liver	309.0	300.9
Lung	76.6	74.6
Trachea	11.9	12.0
Right femur	34.7	33.1
Rib	4.6	4.6
Hilar lymph nodes	0.45	0.40
Mediastinal lymph nodes	0.31	0.30
	Rat	
Lungs	1.77	1.76
Trachea	0.13	0.13
	Burro	
Lungs	1513.0	1517.0
Rib	54.6	55.5
Lymph nodes	3.2	2.6
	Sheep	
Lungs	368.9	362.7
Rib	9.4	8.7
Lymph nodes	1.24	1.25

TABLE 3.6—MEDIAN PLUTONIUM CONCENTRATION IN DOG AND BURRO TISSUES
(Disintegrations per minute per gram wet weight)

Exposure condition	GI tract plus contents	Hilar LN	Mediastinal LN	Lung	Femur	Rib
			Dog			
Acute	25.05	2.05	3.45	0.71	0.046	0.56
1000 $\mu gm/m^2$	4.51	2.05	6.90	0.45	0.057	0.70
100 $\mu gm/m^2$	1.14	3.33	6.90	0.020	0.057	0.48
10 $\mu gm/m^2$	0.25	3.08	3.45	0.031	1.13	0.19
			Burro			
1000 $\mu gm/m^2$		0.62		0.15		0.083
100 $\mu gm/m^2$		0.50		0.032		0.15
10 $\mu gm/m^2$		0.65		0.020		0.18

TABLE 3.7—MEDIAN PLUTONIUM CONCENTRATION IN TISSUES OF ANIMALS PLACED IN FIELD AT P PLUS 32 Days
(Disintegrations per minute per gram wet weight)

Exposure condition	Lung	Hilar LN	Rib
	Sheep		
1000 μgm/m^2	0.093	2.98	0.51
100 μgm/m^2	0.020	2.03	0.24
10 μgm/m^2	0.0011 (0.014)*	1.64	0.50
	Dog		
100 μgm/m^2	0.03	5.81	0.43

*Numbers comprising the median lung values are 0.4, 10, and 0 dis/min. However, the analytical data show that a spill occured with the 0-value. Therefore, values including and excluding (in parenthesis) this value are used.

TABLE 3.8—DATA ON LUNG AND GASTROINTESTINAL TRACT PLUS CONTENTS
(As a function of distance (acute), or isolevel line (chronic), expressed as median disintegrations per minute per organ, GI tract-to-lung ratios)

Location	Lung	GI tract plus contents	Ratio GI to lung
	Acute Dogs		
500 ft	47.5	2742	58
1000 ft	95	72109	760
2000 ft	101	15699	157
	Chronic Dogs		
1000 μgm/m^2	36	2660	77
100 μgm/m^2	1.6	496	310
10 μgm/m^2	2.5	112	45
	Chronic Burros		
1000 μgm/m^2	254		
100 μgm/m^2	41.8		
10 μgm/m^2	27.8		
	Chronic Sheep (P + 32)		
1000 μgm/m^2	34		
100 μgm/m^2	7.0		
10 μgm/m^2	0.4 (5.2)*		

*Numbers comprising the median lung values are 0.4, 10, and 0 dis/min. However, the analytical data show that a spill occurred with the 0-value. Therefore, values including and excluding (in parenthesis) this value are used.

160 days the chronic animals remained in the field. All calculations are made on the assumption that no plutonium leaves any organ throughout this exposure period. There is no factor included in these calculations to account for the actual fraction of released energy reaching the tissue, but such a factor will be introduced later. Because such factors lead to a reduction in tissue dose, dose rates in Table 3.9 are referred to as maximal. For the acute exposure case, the GI tract receives the highest radiation dose by a factor of 10. The chronic dogs all show mediastinal lymph nodes to be the "controlling" organ. Lung and rib, the organs which the National Committee on Radiation Protection used for determination of maximum allowable concentration in air and water, are never controlling organs when considered in this way.

TABLE 3.9—MAXIMAL MEDIAN RADIATION DOSE RATES TO DOG AND BURRO IN REM PER WEEK*

Exposure condition	GI tract plus contents†	Hilar LN†	Mediastinal LN†	Lung	Rib‡
		Dog			
Acute	0.22	0.018	0.031	0.0062	0.025
1000 μgm/m^2	0.040	0.018	0.061	0.0040	0.031
100 μgm/m^2	0.010	0.030	0.061	0.0002	0.022
10 μgm/m^2	0.0022	0.027	0.031	0.0003	0.009
		Burro			
1000 μgm/m^2		0.0057		0.0013	0.0036
100 μgm/m^2		0.0044		0.0003	0.0065
10 μgm/m^2		0.0057		0.0002	0.0080

*RBE = 10; no biological decay assumed.

†No factor for energy degradation within organ.

‡Factor of 5 included to effectively increase dose due to uneven distribution within organ.

To transform the values presented in Table 3.9 from dog to man, one can divide the doses by a factor of two, the logic for which is presented in Table 3.10. These are values assumed for the case of an accident in which a member of the general population is involved, and are as valid as any other known figures for a similar circumstance.

TABLE 3.10—DOSAGE RELATIONSHIP BETWEEN DOG AND MAN FOR THE CASE OF AN ACCIDENT

Man breathing rate is 6-20,000 cc/min. (av. 13,000).
Dog breathing rate is 2.5-3000 cc/min. (av. 2750).
Man inhales 13,000 ÷ 2750, about 5 times as much as dog.
Man lung weights 750-1000 grams.
Dog lung weighs 75-100 grams.
Man lung weighs about 10 times as much as dog lung.

The assumption that respiratory pattern of deposition in lung is about the same in both dog and man is valid. Therefore, for the same atmosphere breathed, the dose to man's lung would be approximately 5 ÷ 10 = 0.5 times the dose to dog lung:

$$\frac{13000}{2750} \times \frac{100}{1000} = 0.473 = 0.5$$

A reduction factor of 20 is generally used when the dose to GI tract from alpha emitters passing through it is calculated, since it is assumed that only 5 percent of the energy released reaches the epithelium, due to absorption of the particle energy in the intestinal contents. Therefore, the doses in Table 3.9 for dog GI tract should be divided by 20 to be consistent with recommended practice. Such a factor could reasonably be applied to lymph node calculations as demonstrated in Fig. 3.1. This is a photomicrograph of a lymph node from a dog which inhaled uranium dioxide for a period of two years on a schedule of six hours each day, five days a week. The black areas in the center are uranium dioxide, and it is evident that a large amount of clumping has taken place. The dark areas at the periphery are the germinal centers where lymphocyte production takes place and are presumably the most radiosensitive part of the tissue. The organ is of such size (diameter approximately 6000 microns) compared to the range of a uranium alpha particle (about 30 microns in tissue), that extremely small quantities of the total energy released would be expected to reach these sensitive areas. Therefore, a factor of 20 to reduce the dose calculated for lymph nodes seems very conservative. There is no reason to believe that plutonium oxide would act differently from uranium oxide in this respect, particularly since uranium oxide is more soluble in body fluids than is plutonium oxide. The factor of 20 for the GI tract is also extremely conservative.

Fig. 3.1—Uranium-burdened lymph node. Illustration shows lymph node of dog that had been chronically exposed to uranium dioxide under laboratory-controlled conditions. Dark areas near center are agglomerates of uranium dioxide. Dark areas near periphery of node are germinal centers. Node is some 6000 μ in diameter.

When these factors for energy degradation and for extrapolation from dog to man are placed in the dosage calculations of Table 3.9, the effective dose rates for man are obtained as shown in Table 3.11. The controlling organ on these bases is rib, the highest lung receiving about one quarter the dose rate of the rib, for the acute exposure. Therefore, by following this reasoning for energy degradation, the critical organ becomes that one originally selected by the National Committee on Radiation Protection for calculation of maximum permissible levels, namely bone, with lung probably being a second choice on the basis of Table 3.11. The highest dose rates obtained are 0.016 and 0.013 rem per week at the 1000-μgm/m^2 line and for the acute case, respectively. Because decontamination teams will be expected to reduce the possibility of chronic hazard within a short time after an accident and because these doses are so nearly alike, the acute exposure probably should be considered the more hazardous. The highest dose rate shown in Table 3.11 is approximately 1/20 of the maximum permissible occupational exposure. This is less than 60 roentgens for a 70-year lifetime if infinite plutonium residence in these organs is assumed. On this basis, there would appear to be no alarming hazard associated with a single detonation of this type under the particular conditions of weather and geography of the Test Group 57 experiment.

TABLE 3.11—MAXIMAL AND EFFECTIVE DOSE RATES TO MAN BASED ON MEDIAN DOG VALUES*

Exposure conditions	GI tract plus contents	Hilar LN	Mediastinal LN	Lung	Rib**
		Maximal dose (rem/week)†			
Acute	0.11	0.009	0.016	0.0031	0.013
1000 μgm/m^2	0.020	0.009	0.031	0.0020	0.016
100 μgm/m^2	0.0050	0.015	0.031	0.00009	0.011
10 μgm/m^2	0.0011	0.014	0.016	0.00014	0.0044
		Effective dose (rem/week)‡			
Acute	0.0055	0.00045	0.0008	0.0031	0.013
1000 μgm/m^2	0.001	0.00045	0.0016	0.0020	0.016
100 μgm/m^2	0.00025	0.00075	0.0016	0.00009	0.011
10 μgm/m^2	0.00007	0.0007	0.0008	0.00014	0.0043

*RBE = 10; no biological decay assumed.

**Factor of 5 used to increase effective dose due to "uneven distribution" in the organ.

†No correction for energy degradation.

‡Correction applied to gastrointestinal tract and lymph node calculations for energy degradation (factor of 20).

3.3 ANALYSIS OF DATA

It appears wise to continue to use the lung or the rib as critical organ and not to change previous thinking at least on the basis of the low numbers which were obtained from this experiment. In fact, because these low numbers will not lend themselves to a readily interpretable statistical analysis, it is difficult to place any quantitative degree of confidence in them. The uncertainties become more evident in Table 3.12. When all median tissue values of 1.0, 1.5, and 2.0 dpm and below are successively considered as background, the fraction of tissue medians which would be eliminated for each exposure condition is appreciable.

TABLE 3.12—FRACTION OF TISSUES OF POSSIBLY INSIGNIFICANT PLUTONIUM CONCENTRATION
(In cases where median tissue contents of 1 dpm and below, 1.5 dpm and below, and 2 dpm and below are considered unreliable)

Significance level (dis/min)	Fraction of tissue medians eliminated			
	Acute	1000 $\mu gm/m^2$	100 $\mu gm/m^2$	10 $\mu gm/m^2$
1	0.3	0.3	0.1	0.4
1.5	0.3	0.4	0.5	0.7
2	0.5	0.7	0.9	0.7

There is adequate rationale for assuming such values to be background on the basis of counting statistics and sensitivity tests[6] and tissue autoradiography (Appendix A). Statistical treatment* of a large number of analyses of spiked samples indicates a sensitivity of 2 dpm, including the counting error. The autoradiographic studies fully bear out such a value, the plates in no case indicating activity above background for tissues, the counting rates of which were at these low levels. To demonstrate this, Table 3.13 presents the median effective dose rates to man when the dog tissues are eliminated on these bases. At the 1-dpm level of elimination, lung is the only organ (with the exception of GI tract) which gives a significant dose rate for all of the exposure conditions, but it is lower than rib for the first three levels. For a 2-dpm limit, lung is the only organ which shows a significant dose rate (again with the exception of GI tract), and even this is eliminated at the 100-$\mu gm/m^2$ line. The bone samples are all eliminated from consideration when this activity level is assumed to be insignificant. The point for emphasis is the fact that a major tissue (bone) could be the controlling organ, depending on whether one chooses to place confidence in 1 dpm or 2 dpm as the significance level. This certainly necessitates a cautious approach in the interpretation of such data.

TABLE 3.13—EFFECTIVE DOSE RATES TO MAN
(When median dog tissue values are eliminated at the 1-dpm and 2-dpm levels)

Exposure condition	GI tract plus contents	Hilar LN	Mediastinal LN	Lung	Rib
		For 1 dpm (rem/week)			
Acute	0.0055	E*	E	0.0031	0.013
1000 $\mu gm/m^2$	0.001	E	0.0016	0.002	0.016
100 $\mu gm/m^2$	0.00025	0.00075	0.0016	0.00009	0.011
10 $\mu gm/m^2$	0.00006	0.00070	E	0.00014	E
		For 2 dpm (ren/week)			
Acute	0.0055	E	E	0.0031	E
1000 $\mu gm/m^2$	0.001	E	E	0.0020	E
100 $\mu gm/m^2$	0.00025	E	E	E	E
10 $\mu gm/m^2$	0.00006	E	E	0.00014	E

*E = eliminated, since activity is not significantly above 1 or 2 dpm

*Dr. Steck calculated that a counting time of about 15 minutes and a critical count of 3 or more would give the counting procedure reasonable statistical properties; that is, if the actual sample rate were zero, there was a probability of 0.90 of deciding thus. If the actual rate were 1/3 cpm, the probability of deciding activity was present was 0.95. If the rate were 2/3 cpm, then the probability of deciding activity was present was 0.99. Actual backgrounds were of the order of 4 counts per hour, and counting times were 16-2/3 minutes (because of timer settings).

If the dose to lung (Table 3.13) were calculated, where an effective half life of 360 days is used, it would deliver a 70-year life-time dose of less than 0.5 rem. Where an effective half-life of 4.3×10^4 days is used, the acute rib would receive a 70-year dose of about 30 rem, with a factor of 5 assumed for uneven distribution.* The decision to be made is whether the rib values are real at 1 dpm. Because there is no obvious pattern of rib buildup in plutonium concentration with time, interpretation of these data on a physiological basis is very difficult. Rib analyses in control animals have shown values of the order of 1 or 2 dpm, but lung values for the acutely exposed animals are clearly significant on any basis. It is difficult to understand how rib values from animals sacrificed at H plus 4 hours would be as large or larger than at much longer times postdetonation. In fact, one would logically expect a correlation between lung and femur and rib concentrations; there is no such correlation. The choice between a possible lifetime dose to the lung of 0.5 rem measured with confidence, or to the rib of about 30 rem (or 6 rem) measured with low confidence, in selecting a critical organ, is not easy when such important decisions rest on the outcome. There is also a possibility that the committees on radiological protection will not use a factor for reduction of dose to lymph nodes for alpha-particle irradiation. If the factor of 20 used here were discarded, then the lymph nodes would most assuredly be the controlling organ by a very large factor.†

3.4 GASTROINTESTINAL TRACT

The gastrointestinal tract and its contents have not been given much consideration here because of the nonphysiological means by which most of the plutonium came to be there. Disregarding this point, some of these data do indicate a decreasing trend with time, which no other tissue shows clearly. When values for a given sacrifice time are plotted, this trend becomes evident for all exposure conditions except the 100-μgm/m^2 line, as shown in Figs. 3.2 through 3.5. Although the lines are drawn by eye and data are quite scattered, half-times can nevertheless be estimated from the curves. The acute data (Fig. 3.2) indicate a very rapid initial decrease in GI tract plus contents ($T_{1/2} \cong 5$ days), which would be expected from animals which were in the fallout pattern. The plot of the data for the lowest isopleth (Fig. 3.3) permits estimation of a half-time of $\approx$ 56 days, which is not unreasonable and may be compared with the air-sample data in Section 4.3 of Chapter 4. This is true, whether the GI tract plus contents burden is derived from inhalation or ingestion. In either case, the decrease in gut activity would be expected to be a function of air concentration. The values of 31 days and 56 days for the 10- and 1000-μgm/m^2 lines do indeed compare favorably with the half-time of 35 days in Fig. 4.3 (Chapter 4).

3.5 LONG-TERM DOG-TISSUE DATA

Tissue data from seven dogs sacrificed 360 days after removal from the field and return to Rochester (520 days after placement) are presented in Table 3.14. The GI tracts still show significant amounts of plutonium. The lungs of four of the seven dogs contained over 2 dpm, and are comparable for all three levels of exposure. The 1000-μgm/m^2 dogs have lost practically all the lung burden they had after 160 days in the field (mean = 83 dpm/lung). No lymph node values are over 2 dpm, but samples were obtained on only four of the seven dogs. The main significance of these data from the 520-day sacrifice is the fact that lungs of dogs exposed at 1000-μgm/m^2 went from a mean of 83 dpm at 160 days to a mean of 1.8 dpm at 520 days, while those at 100-μgm/m^2 went from 15.2 dpm to 2.1 dpm, and those at 10-μgm/m^2 dropped from 8.4 dpm to 1.4 dpm. These values imply considerably shorter half-times for clearance than the one currently in use, amounting to 60 days, 110 days, and 120 days, respectively.

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*There is little convincing evidence for using this factor of 5, and the more realistic life time dose to rib is probably closer to 6 rem.

†Such a procedure, if applied to occupational exposure, would reduce the presently accepted values of maximum allowable concentration for plutonium 239 to such an extent that most work with this material would probably be impossible.

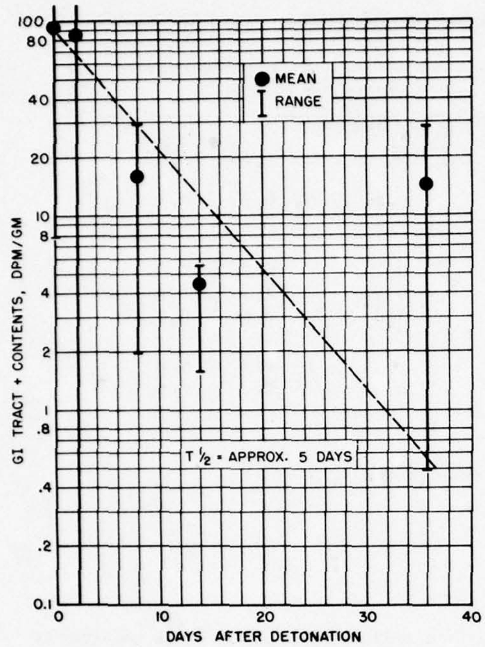

Fig. 3.2—Gastrointestinal tract burdens of acute animals as a function of time.

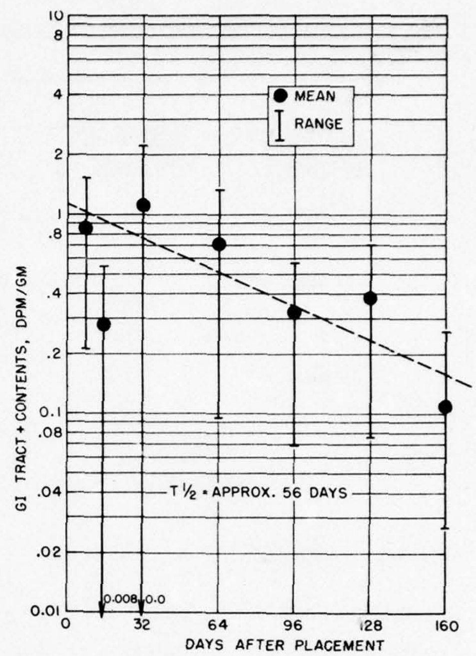

Fig. 3.3—Gastrointestinal tract burdens of 10-μgm/m^2 animals as a function of time.

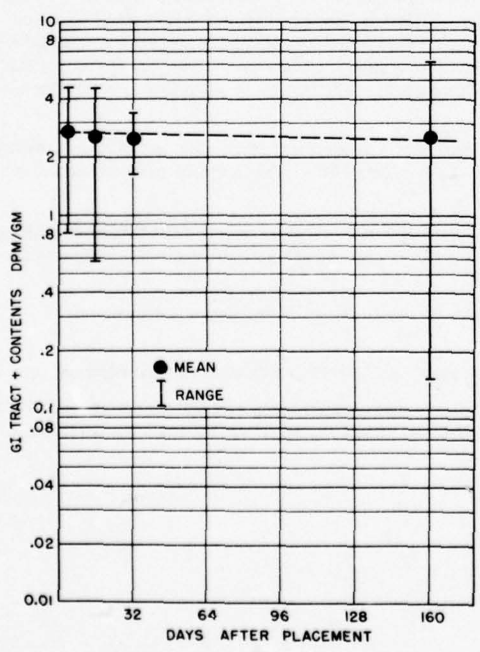

Fig. 3.4—Gastrointestinal tract burdens of 100-μgm/m^2 animals as a function of time.

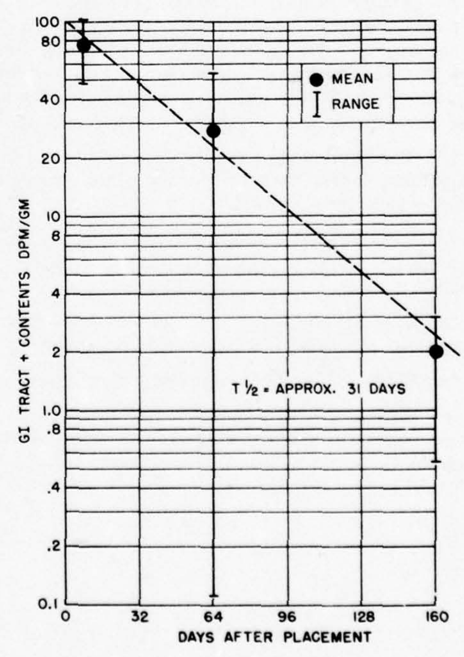

Fig. 3.5—Gastrointestinal tract burdens of 1000-μgm/m^2 animals as a function of time.

TABLE 3.14—TISSUE CONTENTS OF SEVEN DOGS SACRIFICED AT P PLUS 520 DAYS

Exposure condition	Disintegrations/minute/organ				
	GI tract plus contents	Hilar LN	Mediastinal LN	Lung	Rib
1000 $\mu gm/m^2$	40.1	n. s.*	n. s.	0.4	n. s.
	13.3	n. s.	n. s.	3.1	n. s.
100 $\mu gm/m^2$	4.8	0.2	0.2	0.4	0.0
	164.9	0.2	0.2	2.3	0.4
	12.5	0.0	0.0	3.6	0.7
10 $\mu gm/m^2$	7.7	1.7†		0.7	0.0
	5.7	n. s.	n. s.	2.0	n. s.

*n. s. = no sample.

†Definitely LN; undetermined whether hilar or mediastinal.

3.6 SUMMARY OF BIOLOGICAL RESULTS

In summary the following points are of importance:

1. The median is the parameter which best represents the "population" of biological data obtained in Program 72. Quite often the highest value obtained for an organ is chosen for a hazard evaluation, but this procedure can be extremely dangerous, both scientifically and legally. It cannot be disputed that placement of a greater number of animals in the field probably would have resulted in some values even higher than those obtained here. However, the median value for a larger population probably would not differ greatly.

2. Dosage calculation based upon the extremely low numbers obtained in the tissue analyses can give misleading results, particularly if such results should suggest a change in the choice of well-established critical organs. In the future it could easily develop that lymph nodes are the controlling organ for the inhalation of insoluble radioactive materials, but until this is established under better controlled conditions than are found in the field, calculations based on lymph nodes could lead to the setting of levels which would present a real problem in the handling of plutonium.

3. Gastrointestinal tract values obtained from these dogs indicate an accumulation due largely to licking or ingestion rather than to respiratory clearance mechanisms. Therefore, the data are not considered for hazard evaluation for man.

4. The acute case as determined from these data appears to be the more hazardous, and the controlling organ should probably be the lung. This choice is based on the following negative reasoning with respect to the rib:

(a) The rib and femur values show no consistent relationship to each other from animal to animal, although such a relationship would be expected.

(b) If all values of 2 dpm and below are considered insignificant, all median rib values are eliminated.

(c) There is no plutonium buildup in rib with time in the field, even though lung and GI tract were acting as reservoirs for such a possibility. Rib values at less than H plus 4 hours were often as high as at H plus 160 days.

Chapter 4

AIR SAMPLING PROGRAM

In an experiment of the type under consideration here, knowledge of air concentrations of contaminant is perhaps of less importance from the practical standpoint than is the case for more refined laboratory inhalation experiments. In the latter, every effort is made to control concentrations within narrow limits, and particular care is exercised to ensure uniformity of particle-size distribution. In a field test of this kind, the experimenter is wholly at the mercy of the elements, and extreme variability of important parameters is likely to be the rule. It is not impossible, however, to obtain useful information relative to a problem, such as posed by an accidental release of contamination, solely on the basis of tissue burdens and duration of exposure. Consequently, initial planning did not call for an estimation of air concentrations or particle size of the aerosol to which the animals would be exposed.

Before release actually occurred, however, it was determined that air-sampling equipment would be available and power could be supplied to the animal stations, and it was decided that even erratic information over the course of the long-term exposure would be preferable to no information. As a result, an air-sampling program was designed into the biomedical program.

4.1 AIR SAMPLING PROCEDURES

The original plan called for the installation of cascade impactors at each dog station at 2 feet and 5 feet above terrain. Clean slides and Millipore* filters were to be carried out to the field each day by the dog-care crews, exchanged for the exposed slides and filters, and the latter returned to Mercury for subsequent shipment to Sandia for analysis. The purpose of using two heights was to allow for an estimate of the concentration breathed by the dogs and a comparable estimate of what would have been breathed by a man at the same location.

Even before the air sampling program was under way, it was determined that the cross contamination would be far too high if the sample collectors were changed in the field as outlined, and the plan was modified so the impactors were mounted only at the 5-foot level. Sample change was accomplished by exchanging the entire impactor body for one which had been prepared under clean conditions in Mercury. Because of equipment limitations, eight stations were finally established, one at each of the dog stations on the 10- and 100-$\mu gm/m^2$ lines and one on each end of the 1000-$\mu gm/m^2$ cage array, since the latter cages were in close proximity to each other.

Ground-laid power lines were run to these stations from a central generator, where an operating log showed daily performance characteristics of the power net. Because of the extreme length of line for power distribution under these conditions, some difficulty was experienced as a result of low voltage at the sampling stations. A subsequent evaluation, however, showed that if voltage were high enough to operate the Gast pumps at all, without blowing the fuses installed on each pump, they would run at speeds sufficient to pull the proper volume of air through the impactors.

Sample preparation at Mercury consisted of inserting clean slides coated with a thin film of alkyd resin (DuPont No. R1-33) and a clean Millipore filter into each impactor and sealing the complete assembly in a polyethylene bag. At each station, the exposed impactor was exchanged for the unused sampler, care being taken to prevent accidental internal contamination of either impactor. When returned from the field, the used impactor was removed from its bag and the sample collectors carefully removed. Since analyses were to be

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*Millipore Filter Corporation, Watertown, Massachusetts

performed at Sandia rather than at Mercury, preservation of the sample integrity and identity was of utmost importance. This was accomplished by placing the sticky sides of the slides against a small polyethylene bag to which they adhered, and inserting the Millipore and an identifying tag inside the bag. Although this procedure achieved its purpose, it eliminated any possibility of analyzing the samples by direct counting techniques, and it was necessary to perform chemical analyses for plutonium on all of them. Because of the tremendous number of these analyses, it became necessary to pool samples from some stations by weeks. Although this served to increase reliability of such pooled samples by increasing the amount of plutonium per analysis, it did eliminate all indication of the fine structure of concentrations during the week. As will be seen subsequently, however, this shortcoming loses significance in the present case.

As a result of several unexpected delays, it was not possible to initiate the air sampling program until nearly a month had elapsed following detonation. Several of the impactors had been severely damaged during Shot Day operations and had to be repaired. A number of pumps required servicing to give assurance of reliable operation for long periods of time. By May 17, however, all impactors and pumps were in order, and the first of a long series of air samples for concentration and particle size were drawn.

4.2 METEOROLOGICAL VARIABLES

The amount of plutonium to which animals and samplers could be exposed is governed in large measure by meteorological and micrometeorological considerations. Precipitation, local disturbances, and wind speed and direction in particular, assume major significance.

Precipitation throughout the exposure period was minimal; for the five and one-half months of this experiment, rainfall totalled 1.16 inches. As far as can be determined, in view of other more extreme variations, this limited rainfall had no effect on air concentrations. This probably can be explained by the porous nature of the uppermost soil layers of this valley and by the notoriously low desert humidity. It can be reasoned that these trace amounts of rain moistened the top layers, but that the soil-air interface, the truly significant layer in terms of aerosol generation, dried very rapidly, and any soil cohesion developed by moistening was quickly nullified.

Local disturbances, chiefly in the form of "dust devils," are common throughout desert valleys during the summer and can generate extraordinarily high air concentrations. This condition arises from extreme instability of the atmosphere at the lowest altitudes, with subsequent atmospheric upset, the lower levels rising rapidly to altitudes of a few tens to a few hundreds of meters. The upset generally takes the form of a vortex, and its tornado-like action can hoist remarkable amounts of material into the air. On at least one occasion, a large dust devil was seen to pass directly through the 1000-μgm/m^2 cage array.

By coincidence, the dog-care crew was working at these stations at the time. It is significant that, although these men were heavily contaminated superficially, decontamination presented no problems, indicating that the activity was associated with large particle sizes. This is perfectly reasonable. Such atmospheric upsets are so intense that sand, pebbles, and brush are occasionally thrown up, and the great majority of the fine, respirable sizes accumulate at the top of the cloud. In spite of their prevalence, dust devils probably made little contribution to the lung burdens of the experimental animals or to the air samplers; although, because of heavy local fallout, skin-surface contamination and subsequent gastrointestinal uptake as a result of licking may have been high fairly frequently.

Normal winds are of much more concern in the day-to-day resuspension of respirable particles. Cowan[1] has shown that, although there is some dependence on wind velocity (approximately to the first power), there is also a strong dependence on wind direction, particularly in relation to upwind ground-level contamination. As far as particles of respirable size are concerned, settling velocities are so low that, once resuspended, they tend to remain in the air and traverse considerable distances before being redeposited. This, then, requires a summation which is a function of the geometry and magnitude of ground contamination and wind direction relative to the point of interest. Neglecting redeposition for the moment, it can be seen that, following Cowan's line of argument, air concentrations would increase, moving downwind over the contamination field with maximum concentration occuring at the downwind edge. Redeposition does occur, of course, and downwind concentrations would be reduced accordingly. Although not quantitated, the contribution to reductions in air concentrations over distances comparable to those of concern in the biomedical program is relatively minor.

The above discussion takes on major significance when the locations of the dog stations are considered. As mentioned earlier, the findings of Program 74 were relied on for definition of the location of the 10-, 100-, and 1000- gm/m^2 isopleths. On the basis of meteorological advice, the dog stations were located on these lines in a generally northeasterly direction from ground zero. It developed, however, that the winds were not south-westerly, as expected, but actually southerly (between south-southeast and south-southwest) almost

60 percent of the time of the experiment. Winds of predicted direction occurred less than 10 percent of the time. When reference is made to the fallout pattern, it can be seen that locations due north or even north-northwest of ground zero would have been preferable for maximizing exposure with such a wind frequency. The 10- and 100-$\mu gm/m^2$ locations actually are not greatly different in this light, because of the relatively uniform width of the eastern sector of the isopleths and the fact that a south wind blowing over any of the dog stations on these two lines misses areas of heavy contamination.

In any interpretations of results of either the animal or air sampling programs, therefore, it must be remembered that the conditions of exposure for the chronic case do not represent the maximum situation, even for this particular detonation. Furthermore, release and deposition for this experiment occurred under fairly high wind-shear conditions, and under a low-shear regime the more idealized, cigar-shaped isopleths would be obtained. If the axis of this fallout pattern coincided with the most probable wind direction, integration downwind from the contamination boundary line would lead to levels of airborne activity much higher than those found here.

4.3 ANALYSIS OF RESULTS

As was expected, results of the air sampling program were highly erratic, and only minimal correlations and interpretations can be made. The problem is particularly acute for the latter part of the experiment, where values are frequently too low to have much significance. A major dilemma, still not resolved, is whether the activity found is present as free plutonium oxide or as oxide plated out on particles of desert soil. That it is oxide is unquestioned; the metal is highly reactive and was released under conditions of high temperature. A few larger particles were found which were obviously discrete bits of plutonium oxide. Some work on this problem has indicated rather definitely that fine particles also are unattached. On the other hand, it has been found that, at least in some cases, activity is associated with soil particles.

Since this divergency of findings is not likely to yield to solution readily, it has been assumed for present purposes that all activity comes from free, unattached plutonium oxide. If it is assumed that there is an upper-size limit for respirable particles (generally taken as 5μ for particles $\rho = 2.5$), then one can say that only particles found on certain latter stages of the cascade impactor are physiologically significant. If, in truth, $\rho = 11$, as would be the case for PuO_2, it can be said that activity on the same latter stages is still physiologically significant, but the diameter of the upper "cutoff" is reduced to 2.4μ. This approach bypasses the problem of pure versus plated plutonium oxides. Considering only the last three stages of the impactor fulfills this condition, and from the data this amounts to approximately one-half the total sample. It should be recognized that particle size considerations are not included, other than in a general way, in the commonly accepted values for air concentrations. Frequently such a refinement is not available in sampling programs designed to estimate hazards, and gross aerosol sampling will lead to errors of estimation which are conservative. In this experiment, size ranges were not only variable but occasionally extreme, and it is believed desirable to consider chiefly the respirable fraction as related to animal exposure.

Particle size determinations were made on as many samples as possible but, because of inadequate samples, this constitutes a rather small fraction of the total number of samples. Determinations were made by a mathematical method* which was less accurate but considerably less tedious than the more usual graphical method. The procedure is outlined below.

As is common in aerosol work, it is assumed that the distribution of size is log normal and may be expressed as

$$F(d) = \frac{M}{\sqrt{2\pi}\,\ln\sigma_g}\, e^{-\frac{(\ln d - \ln dm)^2}{2\,\ln^2 \sigma_g}}, \qquad (4.1)$$

when F(d) is the frequency of occurrence of diameter d, M is the total mass collected, and σ_g is the geometric standard deviation.

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*Developed by T. T. Mercer.

If this function is integrated for the i-th stage of the impactor,

$$\frac{Y_i}{M} = \int_{-\infty}^{C_i} \frac{1}{\sqrt{2\pi}\ \ln \sigma_g}\ e^{-\frac{(\ln d - \ln dm)^2}{2\ \ln^2 \sigma_g}}\ d\,(\ln d), \tag{4.2}$$

where

$\frac{Y_i}{M}$ = fraction of total sample less than size of stage constant for the i-th stage,

and

C_i = stage constant for the i-th stage.

Since the stage constant is defined as the median diameter for a stage, this expression would become, for Stage D, for example,

$$f_E + \frac{1}{2} f_D = \int_{-\infty}^{C_D} \frac{1}{\sqrt{2\pi}\ \ln \sigma_g}\ e^{-\frac{(\ln d - \ln d_m)^2}{2\ \ln^2 \sigma_g}}\ d(\ln d), \tag{4.3}$$

where

f_E, f_D = fraction of total sample on Stages D and E.

If Z is substituted for

$$\frac{(\ln d - \ln d_m)}{\ln \sigma_g},$$

then

$$f_E + \frac{1}{2} f_D = \int_{-\infty}^{C_D} \frac{1}{\sqrt{2\pi}}\ e^{-\frac{Z^2}{2}}\ dZ, \tag{4.4}$$

$$Z_D = \frac{\ln d_D - \ln d_m}{\ln \sigma_g} \tag{4.5}$$

and

$$\ln \sigma_g = \frac{\ln d_D - \ln d_m}{Z_D} \tag{4.6}$$

In solving for actual samples, Stage A is unusable in this or any other technique, since the stage constant is a function of the aerosol presented. When a Millipore is used as a final Stage E, a similar problem exists, since it is essentially quantitatively efficient for all sizes. Therefore, in most cases, Stages B and D were considered in order to give a maximum spread between points:

$$\ln d_m = \frac{Z_D \ln d_B - Z_B \ln d_D}{Z_D - Z_B}, \tag{4.7}$$

$$\ln \sigma_g = \frac{\ln d_B - \ln d_m}{Z_B}, \tag{4.8}$$

Z_B and Z_D being evaluated from tables for the normal probability function.

When solutions by this mathematical technique were compared with those by the more usual graphical methods, it was found that agreement was excellent for samples of reasonable size which, in truth, were log-normally distributed. Since this method in effect describes the midpoint on a line connecting the cumulative percentages for Stages B and D, it gives no indication of any skewing of the distribution, unless it skewed sufficiently that σg is completely unreasonable. The graphical method, of course, allows consideration of all three intermediate stages, and even gives some weight to the first and last stages as well.

In evaluating the air samples for particle size it was necessary to discard a considerable fraction of them for two reasons: the samples were incomplete or zero and, more commonly, they were evidently not log-normally distributed on the five impactor stages, since one stage carried an inordinate share of the total sample. In the latter phases of the air sampling program, airborne concentrations fell so low that stage burdens were hovering about the statistical limits of detection, particularly at the outer stations.

In spite of these limitations and deficiencies of data, certain interesting and useful observations can be made. It should be recognized that unavoidable biasing is present as a result of the necessity for discarding some of the samples discussed above.

Fig. 4.1 is a histogram of mass-median diameters against frequency of occurrence. From this it may be seen that the median diameter for all stations for the duration of the sampling program was very close to 1.5μ, well within the respirable range as described earlier. This is particularly evident for those stations for which there were a large number of analyses (i.e., most samples were done individually, rather than pooled by weeks).

Fig. 4.2, which is a plot of weekly means of mass-median diameters, portrays the perhaps not unexpected finding that although the variation of particle size over the course of the experiment was highly erratic, there was no clear-cut trend toward either larger or smaller sizes with the passage of time. Actually, on the basis of Cowan's argument, there is no reason to expect such a trend, since presumably whatever mechanism leads to natural resuspension of the contaminant is nonvariant with time, the only important variable being the amount of material available for resuspension.

The sampling data are too erratic to establish half-times for the "decay" of air concentrations beyond a very crude estimate. Fig. 4.3 shows the reduction of total weekly sample with time, on the basis of the median of all stations on a given isopleth. Because of the wide variation, the curves are the "best apparent fit," rather than a rigorous treatment.

The half-time for all three sets of stations considered in this way is five weeks. It can also be seen from these curves that there is little agreement between the ratios of ground contamination and the ratios of air concentrations. The ground levels were actually about 2.5, 40, and 560 $\mu gm/m^2$ for ratios between isopleths of approximately 15. Although air concentrations did increase with approach to ground zero, their ratios are closer to 2 to 4 between sets of stations.

Although there are many shortcomings, the impactor, as a first approximation, may be considered as being comparable to a man breathing the same aerosol. The larger particle sizes are not likely to be inhaled by a man, and the same sizes are likely to be removed in the first stages of the impactor. It can be calculated that the largest plutonium oxide particle that may have physiological significance is 2.4μ on the basis mentioned earlier. If d_m is taken as 1.54 and σ is taken as 3.0, on the basis of the computed air samples 50 percent of each sample collected is in the respirable range. It should be recognized that, in arriving at these values for d_m and σ_g, strong biasing again resulted from the necessity for discarding many samples were σ_g was 10 or higher, samples which undoubtedly were not log-normally distributed. Unfortunately, the data are such that no other approach is practical.

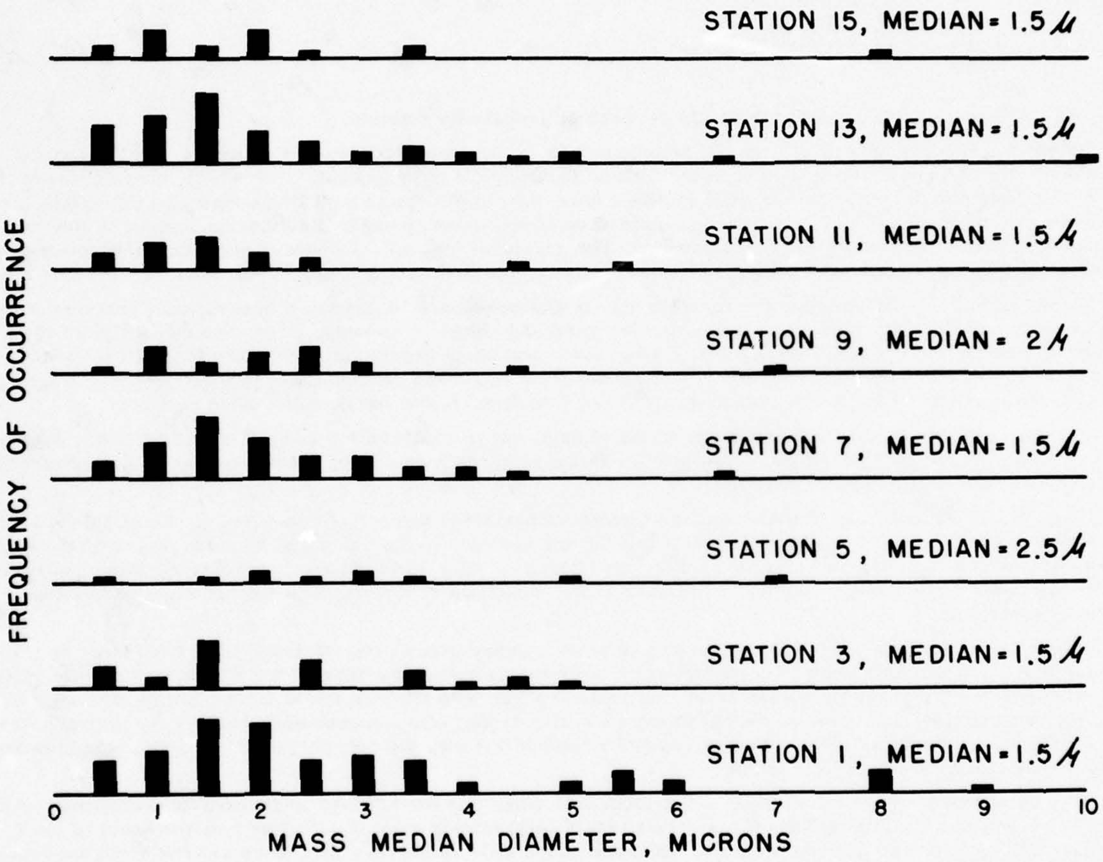

Fig. 4.1—Histogram of frequency of occurrence of stated mass median diameters. It should be noted that differing numbers of samples were analyzed for each station. For example, samples from Stations 1, 7, and 13 were analyzed on nearly a day-by-day basis, while Station 5 samples were pooled by weeks prior to analysis.

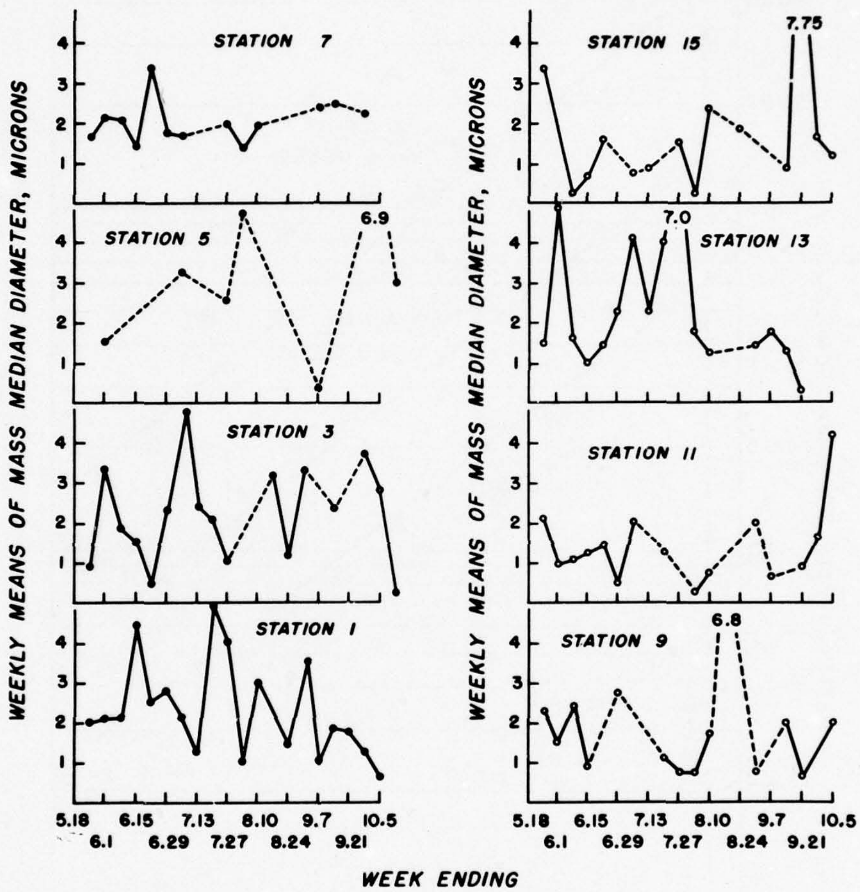

Fig. 4.2—Weekly means of mass median diameters. Although highly erratic, plots indicate there is no clear-cut trend in particle size relative to time. Solid lines connect consecutive weeks, while dotted lines indicate omitted weeks for which data were inadequate.

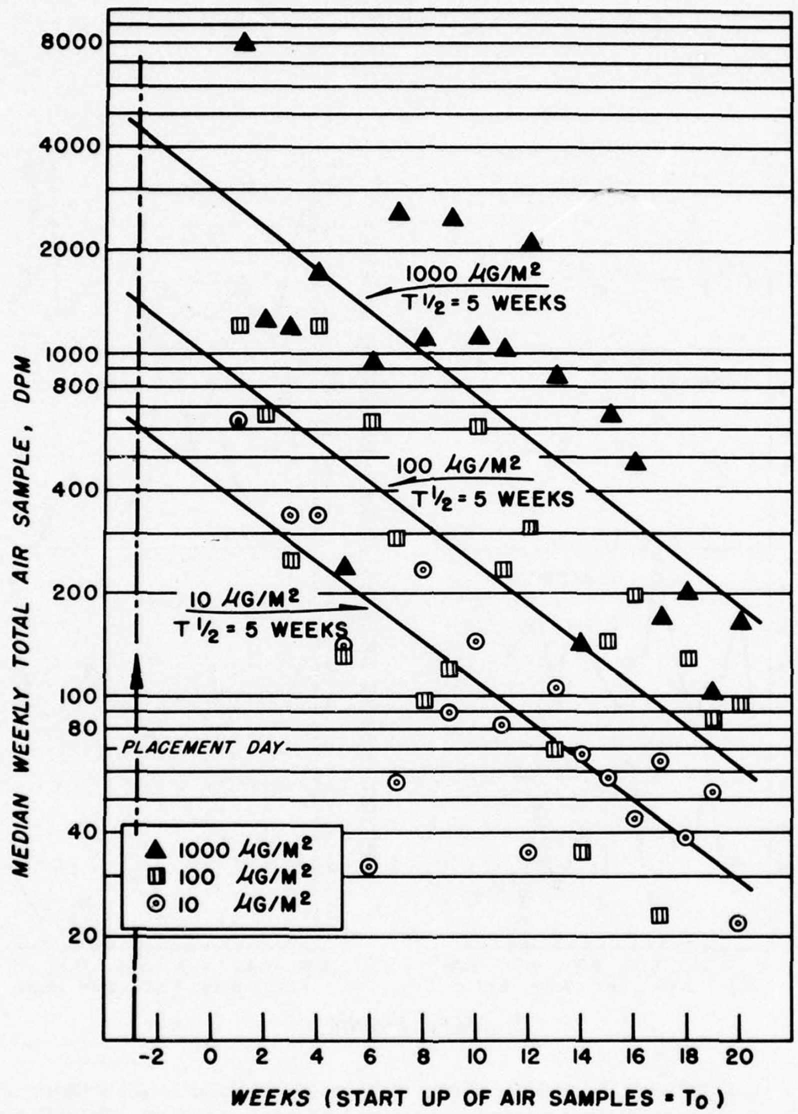

Fig. 4.3—Median weekly air concentrations. Although curves for all three isopleths are shown, their locations and slopes were determined by plotting them separately to minimize inadvertent biasing. It should be recognized that, even though not so drawn, these curves are actually week-by-week step functions.

If the amounts of airborne plutonium to which the animals were exposed is totaled, by summing up the available air-sampler data together with amounts estimated by extrapolating back to the time of placement, it is found that those dogs which were not in the detonation cloud, but which were present for the duration of the chronic exposure, experienced median levels of 4151, 9359, and 30,178 dpm, dispersed in 3.9×10^6 liters (17 dpm for 160 days) on the nominal 10-, 100-, and 1000-μgm/m^2 isopleths, respectively. The cumulative respirable exposure would be one-half these amounts, and the total amount breathed in by the dogs would be $1/2 \times 1/5$, or roughly 10 percent of the amounts sampled by the impactors. Table 4.1 summarizes the information for all exposure periods.

It can be seen that the cumulative air samples build up at a decreasing rate. This rate is plotted for the 10-μgm/m^2 line in Fig. 4.4, which shows that the rate of buildup falls off linearly with a half-time of 35 days. Buildup curves for the other two lines would be parallel to that for 10 μgm/m^2, but offset by the same ratios as those for air concentrations. This curve indicates that the absolute rate of buildup is low, and that it is decreasing at a moderately rapid rate.

It is useful to consider the effect of the rates of lung deposition as derived from air concentration and biological elimination. The data do not permit a rigorous, quantitative evaluation of the combined effect of these opposing mechanisms but, with certain reasonable assumptions, it can be calculated that the peak lung burden occurred either at 103 days or at 126 days, depending on whether the biological half-time for insoluble plutonium is taken as 180 days,[5] or 360 days.[10] The chief assumptions in this calculation are that (a) lung deposition is a constant fraction of inhaled aerosol, regardless of concentration, and (b) elimination from the lung is a constant fraction of the total lung burden.

By use of the experimentally determined, air-concentration decrease half-time of 35 days, the combined effects of the two mechanisms are plotted in Fig. 4.5 for both 180- and 360-day biological half-times. The ordinate is plotted in arbitrary units which are, however, related to lung burden. To quantify this axis, it would be necessary to define lung deposition with considerably more precision than this experiment permits. Such a quantification, though, would not change the basic concepts brought out in this figure. As long as the half-times used are unchanged, the time to maximum lung burden is unchanged, and as the curves show, this time is relatively insensitive to the biological half-time. The mathematical derivation for these curves can be found in Appendix B.

In considering Fig. 4.5, it is apparent that for the first two months of exposure the rate of buildup of the cumulative aerosol concentration is controlling, the lung burden reaching 0.5 of the maximum in 18 days (23 days for $T\ 1/2 = 360$ days) and 0.9 of the maximum in 55 days (68 days for $T\ 1/2 = 360$ days). By this time, however, the lung burden is coming more and more under the control of the elimination process. By the end of the experiment (160 days), lung deposition, day by day, constitutes a very minor contribution to the lung burden, and from this time on lung burden is essentially a function of the biological half-time for insoluble plutonium.

It is important to bear in mind that this approach is basically a "thought experiment." Nothing in the biological data actually bears out such a line of reasoning. Intuitively, it is completely rational; more data, from lungs and air samples containing considerably greater amounts, would be necessary to test this hypothesis.

In summarizing results of the air sampling program, it is fair to say that although the data are not all that might be desired for a rigorous definition of aerosol characteristics throughout the 160 days of exposure, by suitable "smoothing" techniques it is possible to eliminate some of the confusion attendant on the raw data, and indeed to achieve rational after-the-fact explanations of the biological findings which are at some variance with prerelease expectations. Prior to this experiment, it seemed not unreasonable to assume that exposures would be fairly closely related to ground contamination, the thinking being that the immediate surroundings made the major contribution to air levels at a particular station. Following this reasoning, locations were selected to give a minimal spread of two orders of magnitude between the highest and lowest ground levels. The actual spread turned out to be over 200, which would lead one to expect further enhancement of the differences between locations. Actually, however, the spread in air levels appears to be closer to 7 between the highest and lowest isopleths. This spread is too narrow to be explained away simply on the basis of the wide variability of the air data, and it is necessary to reconsider the original assumptions regarding the interplay between ground levels and micrometeorology.

Cowan's analysis accomplishes this with admirable success, even though it is incomplete with regard to redeposition of airborne material. With this approach it is evident that, although the surrounding ground levels are of some importance in determining air concentration, the overriding factor is the history of a parcel of air as it relates to passage over contaminated areas prior to arrival at a particular sampling station. In these terms, a great range between collections at stations on the various isopleths should not be expected. Indeed, had the stations been properly aligned with regard to the prevailing wind direction for this period, air concentrations at the various stations might have increased with distance from ground zero, unless redeposition becomes controlling in this relatively short distance.

TABLE 4.1—SUMMARY OF EXPOSURE PERIOD SAMPLER INFORMATION

		$10\text{-}\mu gm/m^2$		$100\text{-}\mu gm/m^2$		$1000\text{-}\mu gm/m^2$	
Days after placement	Total air sampled* (lit)	Total air concentration† (dpm)	Total inspired acitivity‡ (dpm)	Total air concentration (dpm)	Total inspired activity (dpm)	Total air concentration (dpm)	Total inspired activity (dpm)
4	9.8×10^4	313	31	857	86	2277	228
8	1.9×10^5	620	62	1653	165	4507	451
16	3.9×10^5	1149	115	2846	285	8356	836
32	7.8×10^5	2000	200	4761	476	14543	1454
64	1.6×10^6	3088	309	7197	720	22449	2245
96	2.4×10^6	3667	367	8553	855	26656	2666
128	3.1×10^6	3984	398	8995	900	28964	2896
160	3.9×10^6	4151	415	9359	936	30178	3018

*Based on 17 liters per minute, for the number of days indicated. Note that the samplers were not started until 18 days after placement day, but for purposes of this table volumes are calculated as though sampling was initiated at the same time as animal placement.

†All totals obtained by extrapolation back to placement day in order to account for the first 18 days (cf. Fig. 4.3).

‡Total inspired activity (as distinguished from activity deposited in the respiratory tract) is derived by assuming a breathing rate that is roughly one-fifth the sampling rate, and a respirable fraction that is about one-half the total sampled activity.

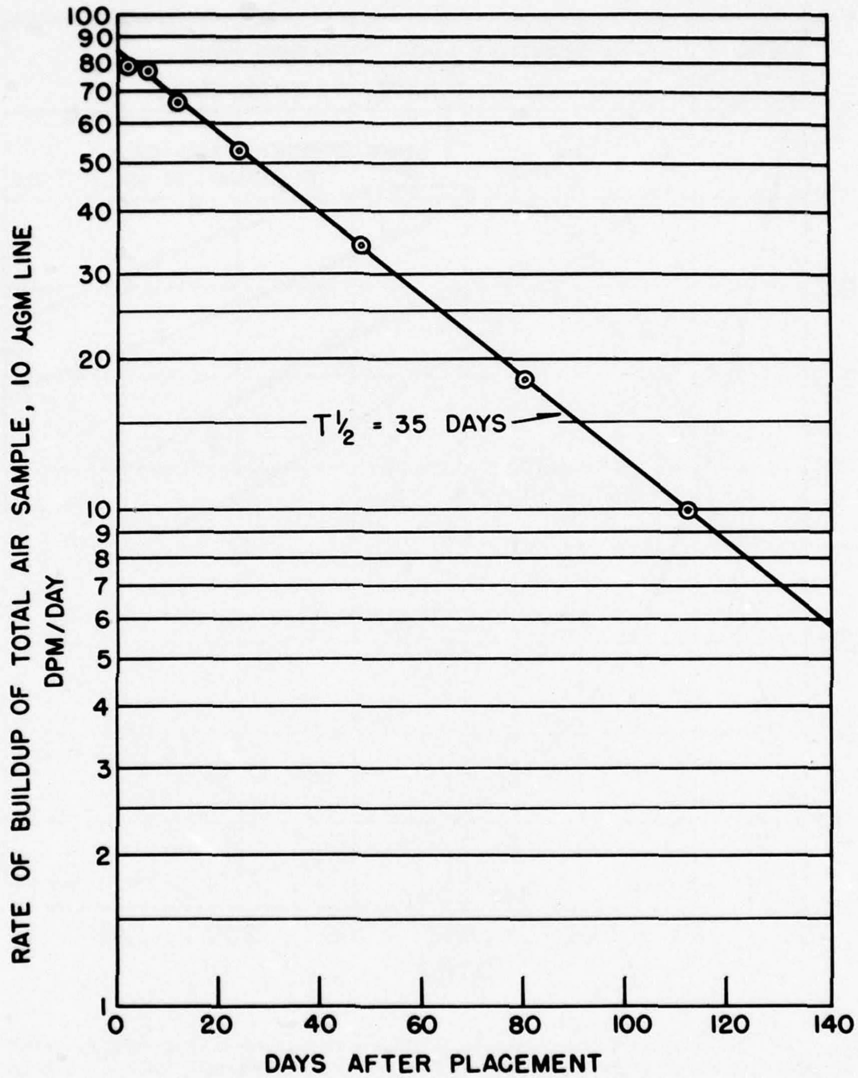

Fig. 4.4—Rate of buildup of total air sample for 10-μgm/m^2 line. Data for first 20 days were determined by extrapolation. Curve shows clearly rapid decrease in rate of accumulation of plutonium by air samplers.

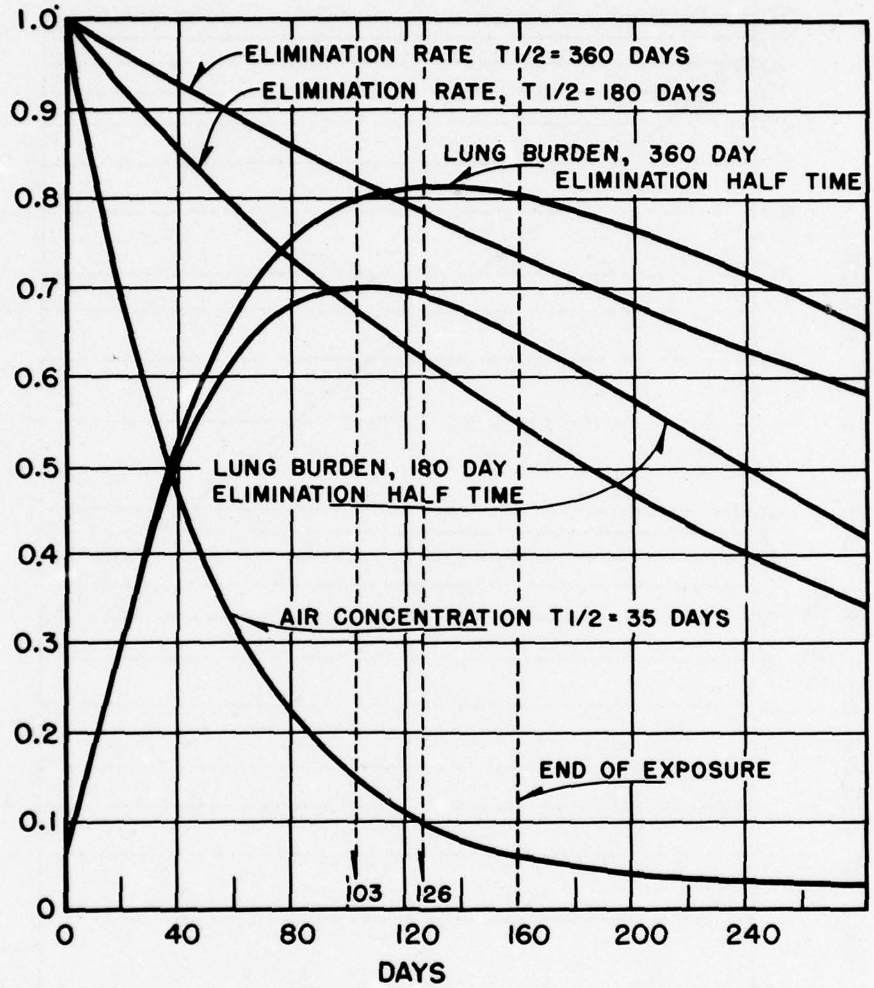

Fig. 4.5—Rate curves for determination of time to maximum lung burden. The ordinate is divided in arbitrary units for normalizing purposes. Doubling elimination halftime has only modest effect in shifting time to maximum lung burden or in raising amount in lung at that time. It is also apparent, for either rate of elimination at the termination of exposure, lung burden was essentially under control of elimination rate; continued exposure would have had little effect on magnitude of lung burden.

When consideration is given to the characterization of the exposure from a particle size standpoint, the completely reasonable finding that neither distance from ground zero nor time after release seem to have any effect further strengthens the expectation of reduced dependence of concentration on distance. There is no question but that the mass-median diameter for all plutonium at a given station was larger closer to ground zero, but a major fraction of this larger material was airborne only in the initial cloud and, once deposited, probably remained in situ throughout the test period. A change in particle size with either distance or time would indicate either an unreasonable change in the resuspension mechanism or a change in the resuspended population. The latter is not impossible from a time standpoint but, when considered with regard to distance, implies a greatly reduced dependence on upwind conditions. The constancy of particle size, then, bears out the Cowan approach.

The unfortunate choice of locations for the chronic stations has been discussed and needs further consideration only to the extent that if, for example, the 10-$\mu gm/m^2$ array had been due north of the 100-$\mu gm/m^2$ array, there might well have been even less difference between the two. Since the outermost stations were somewhat east of due north, parcels of air blowing toward them from the south experienced lower cumulative ground levels as they traversed the fallout pattern than did similar parcels moving towards the 100-$\mu gm/m^2$ stations. Yet, in spite of this, and in spite of the considerably greater opportunity for redeposition in moving to the more remote stations, the ratio of cumulative air levels is less than 4.

Considering all the air data with regard to distance, it is now possible to explain the lack of distance dependence in the experimental animals. Indeed, ratios between the high- and low-level lungs and GI tracts are not greatly different from the ratio of corresponding cumulative air samples, biological ratios being a factor of 2 higher than the sampler ratio. In view of the shortcomings of both biological and air sampling data, such a discrepancy may be considered agreement.

Lack of dependence on time is not so easily explained. It must be noted, however, that although exposure increases with time, the daily increment of exposure decreases. This is quite different from the usual laboratory inhalation experiment where the daily increment is carefully maintained at a constant amount. Air sampling data show that there should be a certain amount of time dependence (roughly, a factor of 10 from start to finish), but apparently metabolism and biological variation obscure this entirely. No tissue except GI tract shows any significant trend, let alone by a factor of 10. The special case of GI tract has already been discussed in detail (Section 3.4). The important point, however, is that time dependence would be expected to be much lower in this experiment than for a laboratory experiment covering a comparable period of time.

REFERENCES

1. Cowan, M.; Plutonium Contamination from One-Point Detonation...etc., WT-1510, Sandia Corporation, Albuquerque, New Mexico; August 1960.

2. Baker, G. P., Jr., and Dick, J. L.; Monitoring and Decontamination Techniques for Plutonium Fallout on Large-Area Surfaces; WT-1512, Sandia Corporation, Albuquerque, New Mexico; August 1960.

3. Butler, R. E., and Miller, H. M.; Surface Alpha Monitoring as a Method of Measuring Plutonium Fallout; WT-1513, Sandia Corporation, Albuquerque, New Mexico; August 1960.

4. Shreve, J. D.; Report of Director, Test Group 57; WT-1515, Sandia Corporation, Albuquerque, New Mexico; (to be published).

5. Harris, P. S., Anderson, E. C., and Langham, W. H.; Contamination Hazard from Accidental Non-critical Detonations . . . ., LA-2079, Los Alamos Scientific Laboratory, Los Alamos, New Mexico; September 1956.

6. Everett, R. J., and Drake, R. W.; Test Group 57 Radiochemistry; SCTM 369-59(51), Sandia Corporation, Albuquerque, New Mexico, March 1960.

7. Merritt, M. L., Cowan, M., Reed, J. W., and Shreve, J. D.; Airborne Plutonium from Weapon Accidents; SC-4326(TR), Sandia Corporation, Albuquerque, New Mexico; July 1959.

8. National Bureau of Standards Handbook 69, 1958.

9. Thomas, R. G., and Wilson, R. H.; Field Studies of Fission Product Inhalation, Part III: Fission Product Field Release Test, Series One (FPFRT-I), Ur-555, University of Rochester, Rochester, New York; 1958.

10. National Bureau of Standards Handbook 52, 1953.

APPENDIX A

AUTORADIOGRAPHIC EVALUATION OF TISSUES FROM PROGRAM 72 ANIMALS*

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A.1 INTRODUCTION

This report is based on the detailed examination of autoradiograms made of tissues of animals sacrificed after varying periods of exposure to the plutonium-contaminated atmospheric and ground conditions of the Test Group 57 project.

While the radiochemical analysis of tissues gives the quantitative information of distribution of plutonium in whole organs of the experimental animals, it cannot reveal distribution of the material within a *single organ.* It was for this reason that the autoradiographic work was undertaken.

A.2 METHODS AND MATERIALS

As animals were sacrificed, small samples of various organs were taken for autoradiographic study. Tissue samples from a total of 40 rats, 84 dogs, and 9 burros were used. The animal tissues examined are given in Table A.1.

TABLE A.1—TISSUES EXAMINED BY AUTORADIOGRAPHY

Tissue Sample		Animal		
Sample	Type of Tissue	Rat	Dog	Burro
Lung A	Respiratory, from lower lobe	X	X	X
Lung B	Respiratory, from upper lobe	X	X	X
Lung C	Air passage, from hilar area		X	
Lung D	Air passage, cross section of trachea near bifurcation	X	X	
Lung E	Hilar lymph node		X	X
Spleen	Surface sample		X	
Kidney	Cortex and medulla		X	
Liver A	Surface sample from right major lobe		X	
Liver B	Internal sample from left major lobe		X	
Number of animals		40	84	9

All samples were fixed in neutral 10-percent formalin, dehydrated in alcohol, and embedded in paraffin.

In the preparation of the autoradiograms, serial sections 7 microns thick were floated onto 1- x 3-inch N.T.A. nuclear track plates,† after the methods of Endicott and Yagoda,[1] and Evans.[2] An emulsion thickness of 10 microns was used. Four sections of each tissue sample were so prepared. The plates were placed in light-tight boxes containing a desiccant and stored in a refrigerator for exposure.

*The autoradiographic program was accomplished under the direction of Dr. Louis J. Casarett of the University of Rochester

†Eastman Kodak Co., Rochester, New York

Autoradiograms were developed at 68 degrees F in D-19* for 5 minutes, rinsed in water, fixed in Acid Fixer* for 20 minutes, and then washed in running water for at least one hour. Tissues were stained in Harris' hematoxylin and alcoholic eosin.

A. 3 RESULTS

Autoradiograms of tissues of rats, dogs, and burros were examined after photographic exposure times ranging from 30 days to 12 months. The shortest exposure time (30 days) yielded completely negative results. Even with a year's exposure, the tissues examined exhibited very low activity, often no greater than background. It is on the basis of the plates developed at this exposure time (12 months) that the following results are reported.

A. 3. 1 Rats

No particles were found in any of the lung or trachea sections examined. There were occasional single tracks but nothing of significance. No differences were noted between groups of rats; autoradiograms of the animals on the ground were no different from those suspended from balloons.

A. 3. 2 Burros

No particles were found in any of the lung or lymph node sections examined. Again, there were occasional single tracks but no significant activity.

A. 3. 3 Dogs

Lymph nodes showed no particles at all. Some animals showed single-track populations greater than background, but this finding was neither frequent nor consistent in any single group of animals. Many lymph nodes, particularly those in "chronic" groups showed a considerable amount of dust, both silica and an unidentified darker material. However, no activity was associated with such deposits.

Liver, Spleen, and Kidney -- Findings for liver, spleen, and kidney were essentially negative. No particles were demonstrable, and only rarely could a single-track population be observed which was greater than background.† When this was found, the liver or spleen was the organ involved.

All lung tissue showed a distribution of single tracks associated primarily with the parenchymal elements. However, in these tissues too, there was no population of tracks markedly different from background.

Three very small particles were found in lung sections from three "acute" animals. The largest of these particles (in Dog 1, 500 feet from GZ, sacrificed two days after detonation) gave a count of 1000 disintegrations for the year's exposure. Particles observed in the other two dogs showed even less activity, giving only 240 and 50 disintegrations for the same exposure period.

The lungs of some of the dogs in the "chronic" groups contained a considerable amount of foreign particulate material. In six animals there was some activity associated with some of the particles. The most active of these particles gave about 25 disintegrations for the year's exposure. The majority, however, gave only 5 to 10 disintegrations.

All particles found were always observed either in alveoli or in the transition regions between alveoli and terminal bronchioles.

A. 4 DISCUSSION

Hundreds of tissue sections were examined that showed no alpha activity greater than background. Lung sections, in general, showed more activity than sections from other organs, but even for lung, the level of activity was extremely low.

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*Eastman Kodak Co., Rochester, New York.

†Background was determined by comparing exposed and unexposed areas on the same slide.

Several questions may well be raised as to these results. First, are they in agreement with the radiochemical analysis of the tissues? Second, are they consistent with the environmental conditions to which the animals were exposed?

A. 4. 1 Autoradiography and Radiochemistry

In no case was activity recorded autoradiographically that was not also revealed by the radiochemistry. However, there were a few instances where autoradiograms revealed no activity greater than background in tissue sections taken from organs that gave relatively high counts radiochemically. For example, the liver count for Dog 107 was 30, 900 dpm, but no significant activity was detected in the liver autoradiogram for this animal. This was also true for Dog 19 (liver count: 1797 dpm) and Dog 40 (lung count: 908 dpm).

While generally low levels of activity were reported for the lung by radiochemistry, even lower levels of activity are suggested by autoradiography. This discrepancy in results may have been caused by: (1) some leaching of material during preparation of tissues for autoradiography; (2) a nonuniform distribution of particulate material in the lung; or (3) a combination of leaching and nonuniform distribution.

The lung samples were paired during tissue preparation so that lung A (a sample through the base of a lobe) was processed with lung B (a sample from above the bifurcation), and lung C (a sample from the hilar area containing a large bronchiole) was processed with lung D (so designated for autoradiographic purposes, but actually a sample of the trachea). Thus, lung A and B samples represented respiratory exchange tissue, and lung C and D samples represented air-passageway tissue.

The solutions used to prepare these tissue samples from seven dogs were selected for analysis. Each paired sample was processed separately so that the solution tested was a pooling* of all the solutions used in tissue preparation prior to embedding in paraffin. The plutonium was recovered from the solution by lanthanum fluoride coprecipitation and T. T. A. extraction. It was then mounted on planchets by electrodeposition, exposed to N. T. A.† plates, and the resultant tracks were counted.‡ Results of this analysis are given in Table A. 2

TABLE A. 2—ACTIVITY FOUND IN SOLUTIONS USED IN TISSUE PREPARATION
(Disintegrations per minute in entire sample)

Dog	Respiratory exchange samples	Air-passageway samples
19	0. 02	0. 68
25	0. 00	0. 00
40	0. 01	4. 22
65	0. 00	0. 00
70	0. 00	0. 00
79	0. 00	0. 30
99	0. 00	0. 00

It is readily apparent that the amount of plutonium lost during the processing of respiratory exchange tissue is very small. Only two of the seven solutions analyzed showed any activity at all, and then only 0. 01 and 0. 02 dpm. The loss of material from air passageway is considerably greater, however. Three of the seven solutions contained activities of 0. 68, 4. 22, and 0. 30 dpm.

*This consisted of the three alcohol baths at concentrations of 70, 95, and 100 percent ethyl alcohol used to dehydrate the tissue, and the xylol bath used to clear the tissue.

†Eastman Kodak Co., Rochester, New York.

‡This work was done through the courtesy of Dr. M. F. Milligan and his section (H-5) of the Los Alamos Scientific Laboratory.

Leaching is expressed as a percentage of the activity in the tissue sample which is found in the processing solution:

$$\text{Percent leached} = \frac{\text{Amount of activity in processing solution} \times 100}{\text{Total activity in sample processed}}.$$

Since the total amount of plutonium in each sample is unknown, it is impossible to express these values in terms of leaching with any degree of certainty. Nevertheless, an attempt was made to evaluate the activity found in the processing solutions in terms of (1) a uniform distribution, and (2) a nonuniform distribution of material throughout the lung and trachea.

When a uniform distribution is assumed, specific values can be assigned to the activity found in the processing solutions. Since the weights of the tissue samples are known, as are the weights and total activity of the organs of each dog, the activity per sample can be computed as

$$\text{Activity per sample} = \text{weight of sample} \times \frac{\text{total activity in lung and trachea}}{\text{weight of lung and trachea}}.$$

Expressed in terms of leaching, then, the values in Table A. 2 become:

	Assumed activity per sample		Percent leached per sample	
	Respiratory exchange	Air passageway	Respiratory exchange	Air passageway
Dog	Tissue*	Tissue†	Tissue	Tissue
40	41.99 dpm	19.91 dpm	0.02	21.2
79	6.39	3.03	0	9.9
19	27.13	12.86	0.07	5.3
65	45.55	21.60	0	0
25	12.56	3.69	0	0
70	7.57	3.59	0	0
99	7.45	3.53	0	0

*Average weight 4.24 grams.

†Average weight 2.01 grams.

In one way, these data suggest that leaching is related to the type of tissue being processed; less leaching occurred for respiratory exchange tissue (0 to less than 1 percent) than air passageway tissue (0 to 21.2 percent). In another way, they imply that leaching is quite unrelated to the type of tissue being processed; the difference between two equally active samples of air-passageway tissue can be as great as that found for samples of respiratory-exchange and air-passageway tissue (Dog 40, 21.2 percent versus Dog 65, 0 percent; Dog 40, 0.02 percent versus 21.2 percent).

It can be argued on the basis of tissue structure that leaching is influenced by the type of tissue being processed. In air-passageway tissue we have essentially a tubular structure; in respiratory exchange tissue we have a sponge-like structure. Plutonium in the former would be found only on the inner surface of the tubes from which the material can easily be lost during processing. Plutonium in the latter would be found throughout the mass of sponge-like tissue, and only material akin to the cut surfaces of the sample would be subjected to the leaching effects of the processing solutions. It is reasonable, then, to assume that a greater percentage of plutonium will be lost from air-passageway tissue than from respiratory-exchange tissue.

It is just as reasonable to assume that this differential leaching will occur regardless of how the plutonium is distributed in the lung, but a knowledge of how the plutonium is distributed is necessary before leaching can be expressed in quantitative terms. With structure, tissue preparation, and plutonium content as constants, the activity in the processing solutions should always be a fairly consistent percentage of the activity in the tissue samples. Wide variations would occur only when errors had been made in computing the activity levels of the samples.

It is obvious in the present case that the activity levels assigned to the tissue samples are in error. These were calculated on the basis of a uniform distribution of material throughout the lung and trachea, a concept whose only merit resides in the fact that it does permit the assignment of specific numbers to the lost material recovered from the processing solutions.

If a nonuniform distribution is assumed, it is impossible to convert the values reported for the processing solutions into percentages. Actually, the only indication we have that a tissue sample contained any plutonium is the activity found in the solution used to prepare that sample, and this could constitute from a fraction to 100 percent of the activity originally present in the tissue sample.

The absence of activity in a processing solution could indicate that no leaching had occurred, or that the tissue sample processed contained no plutonium. The fact that leaching was not a constant for comparable tissue samples (same structure and same assumed activity) supports the view of a nonuniform distribution of material in the lung and suggests that many tissue samples processed did not contain any plutonium.

If leaching invariably takes place in the processing of air-passageway and respiratory-exchange tissue, then the processing solution data indicate that only 5 of the 14 supposedly active tissue samples contained any plutonium. If this ratio of "real" to "assumed" activity is representative of all the "active" lung samples processed, it is clear that a far greater number of negative tissue samples than positive tissue samples were prepared for autoradiography.

Thus, the differences between the autoradiography and radiochemical findings may be attributed separately or jointly to leaching and nonuniform distribution of material throughout the lung.

A.4.2 Autoradiography and the Inhalation Hazard

Autoradiographic evidence supports the view that the atmospheric conditions to which the experimental animals were exposed did not constitute a serious inhalation hazard. In support of this view, it can be pointed out that:

1. The overwhelming majority of all autoradiograms examined were completely negative.
2. Very few of the lung autoradiograms showed activity which was significantly different from background.
3. No particles were found in other than respiratory exchange tissues, and then only 9 in the 2800 sections examined.
4. All particles exhibited very low levels of activity: 2×10^{-3} dpm, 4.8×10^{-4} dpm, 1×10^{-4} dpm, 5×10^{-5} dpm, 2×10^{-5} dpm, and 1×10^{-5} dpm.
5. A year's exposure of autoradiographic plates was necessary before even these levels of activity could be determined.

Obviously, leaching of plutonium introduces considerable uncertainty as to the true number of particles involved. When one considers the levels of activity of the particles found in autoradiograms, it is quite evident that more active particles than these must also have contributed to the total lung counts of the dogs.

No matter what the leaching values in Table A.2 represent—the activity of a single or many particles—it is a fact that more plutonium was lost from air-passageway than from respiratory-exchange tissue. If the lung model is used to estimate the number of particles these losses represent, there could be twice as many particles in air-passageway than in respiratory-exchange tissue. Thus, if 4.22 dpm and 0.68 dpm represent twice as many particles as 0.01 dpm and 0.02 dpm, it would follow that the particles from air-passageway tissue carried much more activity per particle than particles from respiratory tissue. These were the particles—the "more active" particles that have to be postulated to account for the discrepancy between autoradiographic and radiochemical results—not found in the autoradiograms. Since these "more active," larger particles were in regions of the lung from which there is rapid clearance, it is doubtful that they represent a very serious radiological hazard.

A.5 CONCLUSION

Fortunately, many different measurements were made of the inhalation hazard. These do not give quite the benign picture of the environment that autoradiography does. However, no measurement suggests that a very serious inhalation hazard existed for the experimental animals in the present study. To this extent, all measurements are in fair agreement.

REFERENCES

1. Endicott, K. M., and Yagoda, H., Microscopic historadiographic technic for locating and quantitating radioactive elements in tissues. Proc. Soc. Exp. Biol. Med. 64: 170-172, 1947.
2. Evans, T. C., Radioautographs in which tissue is mounted directly on the photographic plate. Proc. Soc. Exp. Biol. Med. 64: 313-315, 1947.

APPENDIX B

MATHEMATICAL EVALUATION OF LUNG BURDEN AS A FUNCTION OF TIME*

The air sampling program (Chapter 4) led to the finding that concentration of airborne plutonium decreases with time under conditions obtaining in the Nevada desert. Numerous other studies have shown that lung burdens of insoluble particulates also decrease with time following termination of exposure. Generally, the decrease in both cases is exponential, the amount found at any time t being

$$A = A_o e^{-\lambda t}, \tag{B.1}$$

where A is amount, either of airborne activity or residual activity in the lung, A_o is the amount when t = 0, and λ is the decay constant for the process.

At zero time the lung burden is zero, since the animals had no previous plutonium exposure. After placement, lung buildup commences at a rate dependent on C, the air concentration, and k, a factor accounting for deposition fraction, breathing rate, etc. For purposes of this analysis, k is considered invariant over the course of the exposure. The amount of plutonium deposited at time t therefore is

$$kC = kC_o e^{-\lambda_1 t}, \tag{B.2}$$

where the decay constant, λ_1, is 0.693/35 days, or approximately 0.02 day $^{-1}$.

If L_t is lung burden up to time t, the amount added at time t is kC_t, and the amount of deposited activity removed from the lung by normal physiological processes if $\lambda_2 L_t$, where λ_2 is the removal constant, taken as either 0.693/180 days[1] or 0.693/360 days[2] (0.00385 day^{-1} or 0.00192 day^{-1}). The change in lung burden will be

$$dL = kCdt - \lambda_2 L\, dt, \tag{B.3}$$

or

$$\frac{dL}{dt} = kC_o e^{-\lambda_1 t} - \lambda_2 L. \tag{B.4}$$

The solution of this equation takes the form:

$$L = Ae^{-\lambda_1 t} + Be^{-bt}. \tag{B.5}$$

When L = 0 (at t = 0), A = -B.

Differentiation of (B.5) yields

$$\frac{dL}{dt} = -\lambda_1 Ae^{-\lambda_1 t} - bBe^{-bt}. \tag{B.6}$$

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*The authors are indebted to Dr. James Shreve of Sandia Corporation and Dr. Donald Morken of the University of Rochester Atomic Energy Project for suggesting and developing this approach (cf. Fig. 4.5 of main text).

Substituting into (B. 4),

$$-\lambda_1 A e^{-\lambda_1 t} - bBe^{-bt} = kC_o e^{-\lambda_1 t} - \lambda_2\left(Ae^{-\lambda_1 t} + Be^{-bt}\right). \tag{B.7}$$

From this,

$$-\lambda_1 A = kC_o - \lambda_2 A,$$

or

$$A = \frac{kC_o}{\lambda_2 - \lambda_1} = -B, \tag{B.8}$$

and

$$-bB = -\lambda_2 B,$$

or (B. 9)

$$b = \lambda_2 .$$

Then

$$L = \frac{kC_o}{\lambda_2 - \lambda_1} e^{-\lambda_1 t} - \frac{kC_o}{\lambda_2 - \lambda_1} e^{-\lambda_2 t}$$

$$= \frac{kC_o}{\lambda_2 - \lambda_1}\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right). \tag{B.10}$$

It can be seen that $L = 0$ when $t = 0$ and when $t = \infty$, and has a maximum for $0 < t_{max} < \infty$. The value of t_{max} is obtained by setting the derivative of

$$\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right)$$

equal to zero:

$$\lambda_2 e^{-\lambda_2 t} - \lambda_1 e^{-\lambda_1 t} = 0. \tag{B.11}$$

Multiplication by

$$e^{\lambda_1 t}$$

yields

$$\lambda_2 e^{-\lambda_2 t} e^{+\lambda_1 t} - \lambda_1 = 0, \tag{B.12}$$

or

$$e^{(\lambda_1 - \lambda_2)t} = \frac{\lambda_1}{\lambda_2}. \tag{B.13}$$

Now $\lambda_1 = 0.693/T_1$ and $\lambda_2 = 0.693/T_2$, where T_1 and T_2 are half-times, so that

$$\frac{T_2}{T_1} = e^{0.693\left(\frac{T_2 - T_1}{T_1 T_2}\right)t}, \tag{B.14}$$

and

$$t_{max} = \frac{1}{0.693\left(\frac{T_2 - T_1}{T_1 T_2}\right)} \ln \frac{T_2}{T_1}$$

$$= \frac{T_1 T_2}{0.693\,(T_2 - T_1)} \ln \frac{T_2}{T_1} \tag{B.15}$$

If T_1 is taken as 35 days and T_2 as 180 days, then t_{max} = 103 days; for T_1 = 35 days and T_2 = 360 days, t_{max} = 126 days.

REFERENCES

1. Harris, P. S., Anderson, E. C., and Langham, W. H.; Contamination Hazard from Accidental Non-critical Detonations . . . . ; LA-2079, Los Alamos Scientific Laboratory, Los Alamos, New Mexico; September 1956.
2. National Bureau of Standards Handbook 52, 1953.

APPENDIX C

TISSUE ANALYSIS VALUES

The following Tables, C.1 through C.4, present amounts of plutonium actually found in the indicated tissues. Note that values given are the activity in the sample analyzed, regardless of sample size. Tabulations of activity per gram for the various tissues may be found in Tables 3.1 through 3.4, Section 3.1, of the main text.

TABLE C.1—PLUTONIUM CONTENT IN TISSUES OF CHRONIC DOGS AND BURROS ON THE 10-μgm/m^2 ISOLEVEL LINE*

Dogs

Time of sacrifice	Location	Radioactivity in disintegration per minute									
		Spleen	GI tract	Liver	Hilar LN	Med. LN	Lung	Trachea	Nas. muc.	Femur	Rib
P + 4	54, 48			0.4	0	2	27	0	0.5	4.6	0.8
P + 4	56, 45	0	348	0	0	0.4	0 (sp)	1	0.4	5	2
P + 8	56, 45	0	748	3.7	2	1	2.5	0.9	0	6.8	0.9
P + 8	52, 51	1.5	112	2	0.8	1.5	19	1.1	2.0	2	3
P + 16	52, 51	0.4	352		0	2	5 (sp)	0	2	2	0.4
P + 16	54, 48	1.4	5.0	123	4.5	0.2	0.5	1.8	0.5	17	0.7
P + 32	56, 45	0.7	1088	4.8	0.3	1.0	2.4	0.3	0	19.4	0.7
P + 32	52, 51	0	0	1.8	6.7	405	0	16	0	174	
P + 64	56, 45	0	44 (sp)	1.4	12	0	34	0	18	5.7	15
P + 64	52, 51	0	653	1.2	0.36	0	763	2	0	2	0
P + 96	52, 51	0	229	5.7	4.2	23	3.1	0.5	0	2.3	6.9
P + 96	56, 45	1.8	36	3.9	1.6	0.2	2.5	2.1	0.9	0.5	0.5
P + 128	52, 51		426		2	4	14	0.7	0.9	6	0.8
P + 128	56, 45	0	37	0		1	0	0	1	0	0.4
P + 160	54, 48	0	159	3		0.8	0	0.4	3.5	2	1.4
P + 160	52, 51	2	16	0	2	1	0	0		4.4	1.4
P + 160	56, 45	5	14	1.7		2	33	0	4.4	2	
P + 160	54, 48	0	63	0.7	0.8	1	0.7	0	0.5	37	0.7

*These values do not necessarily represent analysis of an entire tissue, but only that part of the organ on which radiochemistry was performed.

Burros

Sacrifice	Location	Radioactivity in disintegrations per minute		
		Lung	Hilar LN	Rib
P + 160	54, 48	2	1.7	3
P + 160	54, 48	7.7	0.8	9
P + 160	54, 48	46	21	19

TABLE C.2—PLUTONIUM CONTENT IN TISSUES OF CHRONIC DOGS AND BURROS ON THE 100-$\mu gm/m^2$ ISOLEVEL LINE*

Dogs

Time of sacrifice	Location	Radioactivity in disintegrations per minute									
		Spleen	GI tract	Liver	Hilar LN	Med. LN	Lung	Trachea	Nas. muc.	Femur	Rib
P + 4	33, 41	1.1	485 (sp)	11	0	1	0	1	0.8	0.8	5
P + 4	31, 42		2523	5.0	0	0.8	10 (sp)	0	0	1.1	0.5
P + 8	35, 39	3		1.7	0	2.6	1.1	0.5	0.5	4.3	1
P + 8	35, 39	3	1100	0	2	2.6	1.6	3.4	0.7	0.7	8
P + 16	33, 41		352	2	2	0.8	5.5	0.4	4	10	2
P + 16	33, 41	0	238	0	1.4	10.6	58.9	3.2	0	0.7	0
P + 32	31, 42	42	623	24	20	28	0	19	23	31	61
P + 32	35, 39		1909	1.5	6	2	0	0.7	3	0.4	
P + 64	35, 39	0		3.5		5	6	11	2	3	2
P + 64	35, 39	7.5	5.1	0.4	0	0	0.4	3.2	1.0	1.2	241
P + 96	33, 41	0.5	Lost	Lost	1.8	1.8	1.1	1.1	1.4	2.3	1.4
P + 96	33, 41	2	164	0.2	4.3	0.7	1.6	1.8	0.7	0	6.4
P + 128	35, 39	0.7		0	0.8	3	18	0.7	5	4	0.8
P + 128	33, 41	0.7		1	0.8	4	2		4	42	1.3
P + 160	35, 39	0	496	2	0.8	1.5	35	0	1	1.3	2
P + 160	31, 42	1.1	74	2.6	0	2	0	6	2	2	1.5
P + 160	31, 42	0	2583	1	4		10.7	2	0	2.6	0
P + 160	31, 42	0	1066	4.5	7		15	0	13		1

*These values do not necessarily represent analysis of an entire tissue, but only that part of the organ on which radiochemistry was performed.

Burros

Time of sacrifice	Location	Radioactivity in disintegrations per minute			
		Lung	Hilar LN	Rib	Fetus
P + 160	33, 41	15	3	0.8	-
P + 160	33, 41	9	1.4	7	-
P + 160	33, 41	6	1	16	5

TABLE C. 3—PLUTONIUM CONTENT IN TISSUES OF CHRONIC DOGS AND BURROS ON THE 1000-μgm/m^2 ISOLEVEL LINE*

Dogs

Time of sacrifice	Location	Radioactivity in disintegrations per minute									
		Spleen	GI tract	Liver	Hilar LN	Med. LN	Lung	Trachea	Nas. muc.	Femur	Rib
P + 4	27, 35		13198	5	0.8	1.5	22	10	1	1	1.4
P + 4	26, 36	3.0	Lost	Lost		0.7	30	0	0.7	3	0
P + 8	27, 36	0	54545	20		0.7	57	3.8	1.6	4	1
P + 8	26, 36	1.1	16757	1.5	0.8	3	57	2	1.4	2	45
P + 16	27, 35	121		0.7	0.7	0		19.9	0	1.0	0.3
P + 16	26, 36	0.85	6862	2	0	2.6	27.7	5	0.5	0	7.8
P + 32	26, 36	0	2660	3.5	2.1	2	1.6	14	4.2	2	2
P + 32	27, 35	0.7	Lost	5.7	3.2	8.9	45	0	0	7.5	0.9
P + 64	27, 36	0	21301	0	4	3	51	0	0.4	2	3
P + 64	27, 35	1.6	3.7	0	5.4	0		0	4.4	1.7	1.4
P + 96	27, 35	0	3.0	0	1.4	2	36	0	0.2	3.0	1.8
P + 96	27, 35	0	Lost	30900	0.2	0		2.7	0.9	3.7	1.8
P + 128	27, 36	0	2475		0.4	0.8	61	3	0	0.7	3
P + 128	26, 36	0		2.6	1	0	29	0.4	0.4	2	3
P + 160	26, 36	0	818	4.5	1.6		35.5	0.7	1	3.5	
P + 160	27, 36	0	1314	2		5	99	0	1.4	1	2.5
P + 160	27, 36	26	1347	3.7	0.8	2	23	0	0.4	3.5	2
P + 160	26, 36	0	326	9	0	5	173	2	1.4	2	0

*These values do not necessarily represent analysis of an entire tissue, but only that part of the organ on which radiochemistry was performed.

Burros

Time of sacrifice	Location	Radioactivity in disintegrations per minute			
		Lung	Hilar LN	Rib	Fetus
P + 160	27, 36	25	1	3.8	1
P + 160	27, 36	158	1.6	2.6	-
P + 160	27, 36	33	3	6	2.6

TABLE C. 4—PLUTONIUM CONTENT OF TISSUES FROM ANIMALS EXPOSED TO THE CLOUD*

Dogs

Time of sacrifice	Distance from GZ	Location	Radioactivity in disintegrations per minute: Spleen	GI tract	Liver	Hilar LN	Med. LN	Lung	Trachea	Nas. muc.	Femur	Rib
H + 4	500 ft	FW	9	8725		2.7	1.5	64		3.6	8	3
H + 4		FE	92	13750	27	0	4	129		1.4	69	1
D + 2		NW	0	108658	0	1	0.5	48	25	9.3	0.3	0.3
D + 2		NE		0	107	1.8	2	0	4.8	177	10	3
D + 9		FW	0	1184	8	0.8		77	0.4	8.6	9.5	2.5
D + 11		NW	0	2076	6	0.39	0.7	46	0	1	6	3
D + 12		NE	4	2742	1	4	28	47	4	0.5		0
D + 21		FE	0	5591	4	0.35	1.0	1.4	35.5	0.7	0.3	2.5
H + 4	1000 ft	C	0	72109	2.6	0.8	7	170	3	1.7	1	0
D + 2		C	0	89953	0	0.7	1.5	908	424	22	0.3	3
D + 13		FE	0	4210	14	0.5	1	20	0.7	0	3.6	2
D + 21		FW	0.35	0.35		0	6.7	0	2.1	13	2.1	
H + 4	2000 ft	FW	0	45976	3	3.5		41	0.7	33	1	1.3
H + 4		FW	8.8	8950	7	0	0.4	35	0.9	0	1.6	2
H + 4		FE	1.5	79291	0.7	2	0.8	134	6	1.7	0	
H + 4		C	0		2.6			34	0.5	2.3	0	2.5
H ± 4		FE		91812	2	4	1	27	0.9	83	1.4	0.5
D + 2		C		50161	10.5	2.7	4	207	3	90	3	3
D + 8		NE	3	15017	1797		1	475	67	70	25.1	1.3
D + 13		NW	2.3	844	0	0.8	8	155	0.7	0	2	0.8
D + 36		NW	0	16380	3.8	0		68	2.6	1.4	1.5	
D + 36		NE	0	286	2.4	2	0.3	277	0	0	0	0

*These values do not necessarily represent analysis of an entire tissue, but only that part of the organ on which radiochemistry was performed.

Rats
(All sacrificed at H + 2 to H + 4 hours)

Distance from GZ	Location	Disintegrations per minute per lung: Rat 1	Rat 2	Rat 3	Rat 4
500 ft	FW	0	48	1.1	13
	NW	14	0	1.5	0
	NE	45	7.4	0.8	0.4
	FE	0	-	21	1.5
1000 ft	C	0	0	2	4.5
2000 ft	FW	0	2	3	388
	C	0	5	36	0
	FE	2	0		